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Discomfort Glare and the Lighting of Buildings

By P. PETHERBRIDGE, B.Sc., *(Member)*
and R. G. HOPKINSON, B.Sc.(Eng.), Ph.D., M.I.E.E. *(Fellow)*.

Summary

Bright light sources can cause glaring effects which may impair visual efficiency. This may be brought about by a directly disabling effect, or it may result indirectly from irritation and discomfort.

The purpose of the work described in the paper was to obtain more detailed knowledge of the effects of glaring light sources on comfortable vision. A technique of subjective appraisal was used, the basis of which was the control by the observer of a relevant physical variable to give in turn each of a series of precisely defined criteria of discomfort glare.

It has been found that discomfort glare is primarily a function of the balance between the brightness and intensity of the glare source on the one hand, and the brightness of the surroundings on the other, the higher the brightness of the surroundings, the less discomfort will be caused by a given glare source. Due to the limited power of adaptation of the eye, the discomfort caused by large sources of high brightness may not, however, be capable of reduction by increasing the brightness of the surroundings. It has also been shown that small reductions in the brightness of large glare sources, such as windows, can result in a useful decrease in discomfort.

The effect of the displacement of a glare source from the general direction of viewing, the effect of a change of brightness of the immediate surround to the source and the glare effect of a number of sources have been studied.

The relationship between the various physical factors is complex, but the application of the results to problems of lighting design is readily made and is briefly discussed.

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The authors are with the Building Research Station, Garston, Watford. Manuscript first received May 16, 1949, and in final form on September 26, 1949. Presented at a meeting of the Society held in London, January 10, 1950.

(I) Introduction

Modern building practice calls for close links between the factors which govern the efficiency of a building, such as heating, ventilation, acoustics and lighting. A new approach, based on fundamental considerations, is evident in each of these fields. In the field of lighting, engineers and architects have realised that the knowledge of vision which they can glean from the physiologist is incomplete for their purpose, and the experimental psychologist has so far not attempted to tackle the lighting problem on a sufficient scale.

The need to fill these gaps in our knowledge has been intensified by trends in lighting design. It has been a distinctive feature of recent lighting practice that demands must be satisfied for much higher levels of illumination than were previously considered adequate. These improvements in the level of illumination on the working plane constitute a major advance in technique. Good lighting, however, calls for much more than the mere provision of adequate illumination.

Good lighting is, in fact, the provision of a pattern of brightness and contrast which enables the eye to work efficiently and in comfort throughout the duration of the visual task. The practice of lighting is, therefore, to correlate the provision of adequate amounts of light, from windows or from artificial light sources, with the specification of the characteristics of walls, ceilings and of the work itself, to achieve a satisfactory result.

The provision of adequate illumination for the work is still the primary function of the lighting engineer, but the reduction or elimination of glare is of high priority. The recent improvements in working illumination have, however, brought troubles in their train. These higher levels have often been achieved merely by making big increases in the brightness of fittings, or by providing much larger windows. When this has been done, it has been found that, whilst the advantages from the higher illumination levels are marked, the discomfort which results from such large, bright sources of light in the field of view tends to detract from the benefit of the higher illumination.

Economic conditions in the United States of America have permitted the use of higher levels of artificial lighting than are generally common in this country, and so it is from that country that much of the work on brightness and glare has derived. In Britain, the provision of school classrooms with large windows has drawn attention to the fact that in our cloudy climate, large areas of white cloud reach a high and uncomfortable level of brightness all the year round. In this country, therefore, the glare problem is as much one of natural lighting as of artificial lighting.

The glare problem has been studied extensively and, as a result, there is a useful body of information which enables many of the most pressing glare problems to be tackled. This information has not, however, become part of the routine basic knowledge either of the lighting engineer or of the architect, possibly because the glare problem has only recently been of comparable importance to that of the provision of adequate light. It has, nevertheless, long been recognised that the glare problem can be divided into several components, which may conceivably have their origins in different physiological factors. Investigations of the effect of the direct disability which arises from glare, such as those of Holladay [2], [3], Stiles [4], [5], [6], [7], [8], [9], [12], Schouten [13], [14], Ivanoff [23], and other workers, have enabled a clear understanding of the problem to be obtained. Further work is indeed required to confirm that the disability effects which result from large sources can be predicted by a summation calculation from the Holladay formula. Apart from this, the disability problem arising from glare can at the moment be considered to be adequately covered.

On the problem of discomfort arising from glare, previous work has been restricted to limited fields. Holladay's studies were concerned primarily with the

shock effect of a glare source, whilst the work of Harrison [18] was more in the nature of a codifying of existing knowledge, rather than a fresh development. The work of Hopkinson [15] on street-lighting problems dealt with very small, bright sources, but in Hopkinson's paper it was shown that the glare effects of such sources could not all be accounted for in terms of the simplified formulæ of the type first proposed by Holladay. Such formulæ, however, had their value, as they enabled the work to be applied directly to street-lighting designs.

Thus, there was some evidence that any discomfort which arises from glare from a very small source depends primarily on the intensity rather than on the brightness of the source. The discomfort which arises from a large source depends, on the other hand, on both the intensity and the brightness of the source, the effect of the source brightness becoming increasingly significant the greater the apparent area of the source.

It was at this point that the earlier work left the problem. If the indications of the earlier work on the glare from large sources were in fact valid, it was obvious that the simplified expressions derived from these studies could not be applied to the glare problem of windows and other such large sources, and a further experimental programme was necessary.

(II) Experimental Technique

The experimental technique used in the studies reported in this paper is essentially an elaboration of that used in the street-lighting work. In order to investigate glare problems of greater complexity, a more flexible form of the experimental apparatus was required. The description of the apparatus which was given in the street-lighting paper [15] serves, however, to illustrate the present technique. The essential feature is that the observer looks into a model room closed at its far end by a large condenser lens flashed to the required brightness by a projector lamp. In front of this lens

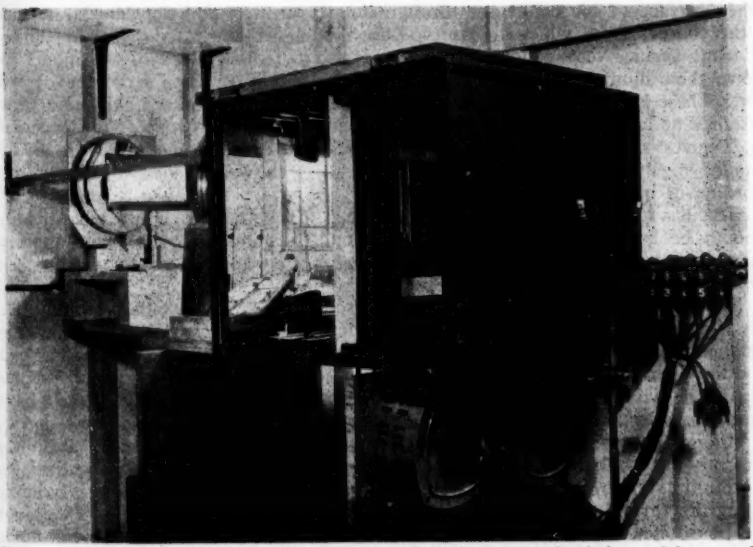


Fig. 1. General view of apparatus for the appraisal of glare, one side of the model removed to show interior.

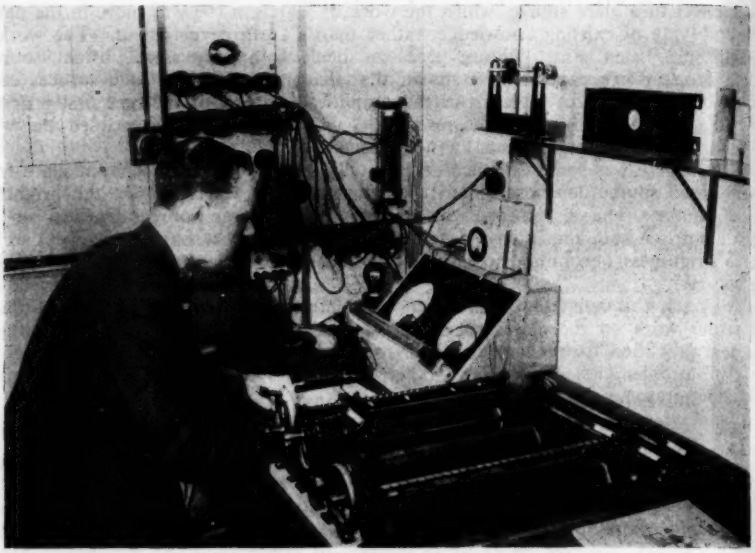


Fig. 2. Control panel and recording position.

is an opaque card which may, for example, be a photograph of a room, apertures being cut out of the card to represent light sources. The observer sees parts of the flashed surface of the condenser through these apertures, and they appear to him to be the sources from which the rest of the model is illuminated. In fact, however, the front surface of the opaque card, and also the other sides of the model room receive their illumination from other lamps which are screened from the observer's view. These lamps, which govern the brightness of the room, are linked to a variable resistance under the control of either the observer or the recorder of the experiment. Fig. 1 gives a general view of the apparatus, one side of the model room being removed to show the interior, while in Fig. 2 is shown the position at which the recording of observations takes place.

The basis of the present studies has been, as before, to apply what has now come to be known as the "multiple criterion" technique of subjective appraisal*. This technique was described in the earlier paper and has been used for a number of investigations during the past ten years with some success.

The observer has a precise degree of discomfort glare described to him. He is then asked to make a setting of the physical factor under his control, e.g., the general brightness in the room, to reproduce this degree of glare. Provided that he has understood the significance of the described degree of glare in relation to his general appraisal of glare, he will not find it beyond his powers to make this setting. If the observer is given a series of criteria, it is found that each criterion acts as a cross check on the others, thus increasing his confidence and hence his competence. Results are thus both more reliable and more comprehensive. The observations obtained using the "multiple criterion" technique enable a series of equal-glare curves to be derived relating the various significant physical factors.

The studies have been made mainly under idealised conditions, that is to say,

* The full description of the present technique is being published concurrently in the Quarterly Journal of Experimental Psychology.

there have been no specific visual tasks given to the observer during the course of his observations. The advantage of experimenting under these conditions is that the physical factors are under control, whereas complications arising from a comprehensive range of working conditions are much more difficult to systematise. The degree of discomfort which can be tolerated under specific working conditions forms part of a study of the glare problem. It raises so many complications, however, that it was felt wiser to confine the present work to easily reproducible conditions, and, except in special cases, to consider the results obtained in relation to working conditions in the light of experience rather than of experiment. Any further advances in the experimental field may be as much in the province of the experimental psychologist as in that of the lighting engineer.

The factor, "discomfort," which was studied, may be analogous to, and possibly identical with, that which in extreme cases we normally call "pain." It is, of course, very rarely that discomfort which arises from glare is sufficiently great to cause pain.

The considerations which arise from the design and placing of lighting fittings and windows have not formed part of the present study, but form an essential part of the lighting work of the Building Research Station.

(III) Accuracy of the Results

One of the major difficulties associated with the investigation of subjective problems of vision is to determine how the experiment should be designed to give the most reliable form of result. The "multiple criterion" technique employs a number of cross checks which assist in achieving a satisfactory approach.

In the first place observers are selected who have the necessary ability to make subjective appraisals, and who are likely as a result, to give more reliable observations. The number of observers used in the present series of investigations was limited to six. A greater number of observers would have been preferred had they been available, but this limitation was offset by the fact that all the observers were experienced in the technique of making subjective appraisals. More observers were originally available, but some had to be rejected as the experiment proceeded because of their inability to make consistent appraisals under constant conditions.

The first task was to familiarise the observers with the experiment and to accustom them to making their own appraisals of glare. They were asked to assess discomfort from the glare source in terms of four recognisable criteria. These were as follows:—

A Just intolerable—the changeover point between intolerable and uncomfortable glare.

B Just uncomfortable—the changeover point between uncomfortable and merely distracting glare.

C Just acceptable—the changeover point between distracting and acceptable glare.

D Just imperceptible—the changeover point where *glare* from the sources is just no longer noticeable; the sources themselves are still noticeable, but they merge into the general field of view in such a way that they no longer form any source of attraction.

One of the essential features of the "multiple criterion" technique is the "Control Experiment." For this control experiment each observer partaking in the main studies makes observations under a set of constant conditions at regular intervals, for example, once or twice every day. Fig. 3 shows the photograph which was used during this experiment, the observers being asked to fixate in the region of the top of the teacher's desk. The control observations continue for the duration of the detailed studies. It is then possible to take a large number of observations made by any one observer under the standard conditions and to find the scatter (or standard deviation) of these observations. If it appears from this control experiment that an observer is

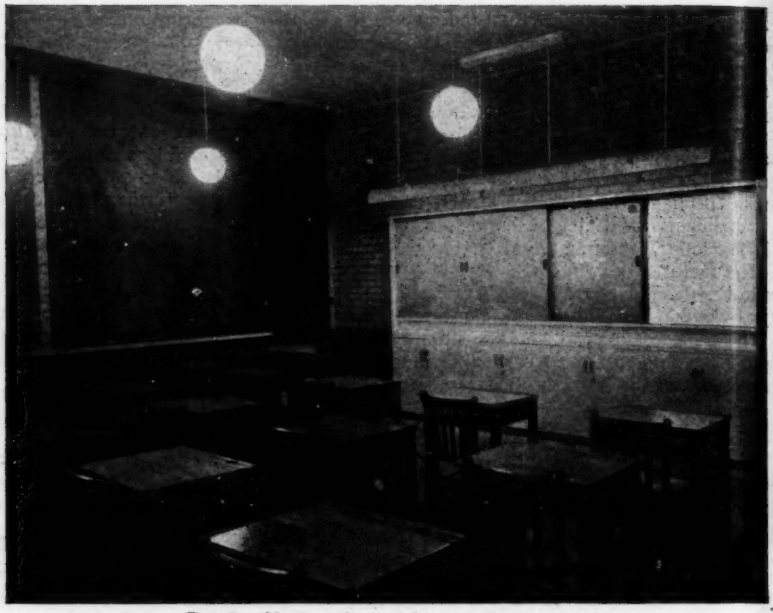


Fig. 3. Glare conditions of 'control experiment.'

unable to make consistent observations he is not employed for the main experiments. The main studies go forward with the smaller number of observers who are able to give more reliable observations. By comparison of the mean of an individual's observations under standard conditions, with a "control experiment" observation made on any specific occasion, it is possible to check each observer's glare criterion, and to make sure that on this particular occasion he is not departing seriously from his normal average.

The variability of a good observer is about ± 0.15 on a logarithmic scale of brightness. The trend of an observer's readings under the standard conditions is illustrated in Fig. 4. This particular observer had a variability of ± 0.16.

This order of accuracy may appear poor to a photometrician, but it is, in fact, sufficient to show up relatively small glare effects successfully. Statistical tests can

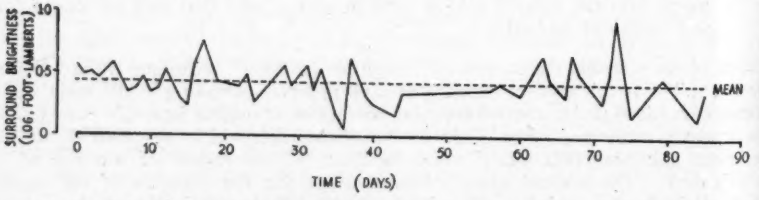


Fig. 4. Typical set of observations of a 'control experiment.' Assessment of surround brightness with which given glare sources give 'just comfortable' glare.

always be applied to reveal whether or not the trend of a series of observations can be considered significant in relation to the known accuracy of the observer.

(IV) Results

The results in general confirm the findings of the previous study on glare from sources in lighted streets, that is to say, the discomfort from a glare source depends on:—

(i) Source brightness, intensity, and apparent area.

(ii) The displacement of the source from the direction of view.

(iii) The general brightness of the surroundings which determines the adaptation level of the eye.

It has also been found of value when discussing glare problems from an architect's standpoint to consider glare as a function of the balance between the brightness and intensity of a source on the one hand, and the general brightness of the surroundings on the other. It is important to note that the surround brightness is that of the general or adapting surround rather than that of the immediate surround of the glare source. (See Section IV (e).)

The main results of the work are briefly given in the following summary. The complete data is very extensive, and is, of course, available for detailed consultation. For the purpose of the present paper, however, it is thought that it would be wise to confine the discussion to general trends. In preparing and averaging the data for this purpose, care has been taken to try to give a balanced picture, but it is recognised that small factors smoothed out from the data may, in fact, be important in some other connotation.

(a) Effect of source intensity, brightness, and area on the discomfort from glare sources

Assessments of discomfort were made by observers with each of five square sources viewed in turn against a uniform background brightness which occupied the rest of the field of view. These five square sources covered a range of 100-1 in area, in steps of $\sqrt{10}$ in area. Their angular subtense at the observer's eye, and the sizes of equivalent sources viewed at a distance of 15 ft., are given in the following table:—

TABLE 1

Sizes of Light Source employed in the Investigation.

Ratio of Areas	Angular Subtense (Steradians)	Equivalent Size at 15 feet
1	2.7×10^{-4}	3 in. square
$\sqrt{10}$	8.5×10^{-4}	5¼ in. ,,
10	2.7×10^{-3}	9½ in. ,,
$10\sqrt{10}$	8.5×10^{-3}	1 ft. 5 in. ,,
100	2.7×10^{-2}	2 ft. 6 in. ,,

The observers were asked to set the surround brightness to correspond to each of the four degrees of glare when the sources had been adjusted to each of five levels of brightness in the range 60—4,500 foot-lamberts.

The data obtained were plotted as "constant glare" curves to show the variation between surround brightness and source brightness and between surround brightness and source area (expressed as the angular subtense of the source at the eye). The data averaged from a number of observations by each of the observers are given in Figs. 5 and 6. It is seen that a change of about 4 : 1 in surround brightness effects a change of one criterion of discomfort. This agrees with the street-lighting studies.

The data of Fig. 7 are the averaged results of a number of determinations for each

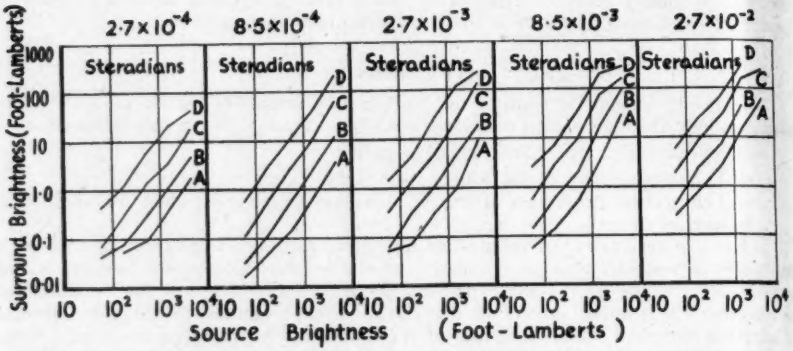


Fig. 5. Variation of surround brightness with source brightness to give four degrees of glare with each of five sizes of square source.

of the observers. In order to give a true picture of the relationship between the source brightness and the surround brightness, it is, however, necessary to take into account not only observations which were made, but also those which could not be made for various reasons. At the lower end of the brightness range, observers found that, no matter how low the surround brightness, they experienced no sensation of discomfort when the source brightness was below a certain level. Similarly, at the highest brightness levels, the glare from the large sources could not be balanced out by the maximum surround brightness which was available. The absence of observations in each case affects the averaged values in such a way as to bias the mean curves in the wrong direction. For this reason the curves of Fig. 7 have been limited to the range of brightnesses over which there are complete sets of observations from all the observers. However, in order to illustrate what is believed to be the true relationship, the remaining (incomplete) sets of readings have been taken into account, and note has also been taken of those occasions when observers expressed their inability to make a setting.

Fig. 8 illustrates this relationship. It shows that the completed equal-glare curves, when plotted with the surround brightnesses as abscissæ and the source brightnesses as

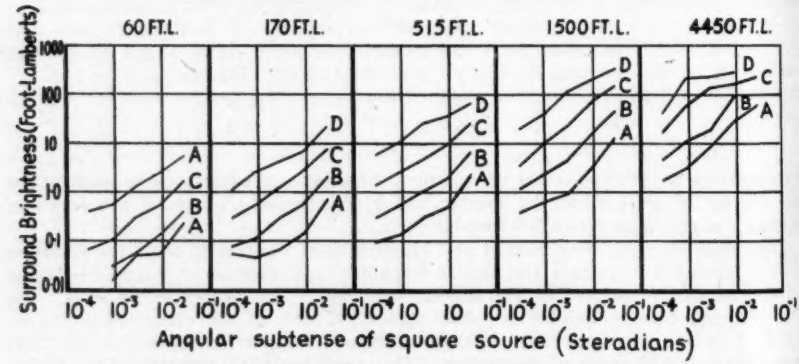


Fig. 6. Variation of surround brightness with size of square source to give four degrees of glare at each of five levels of source brightness.

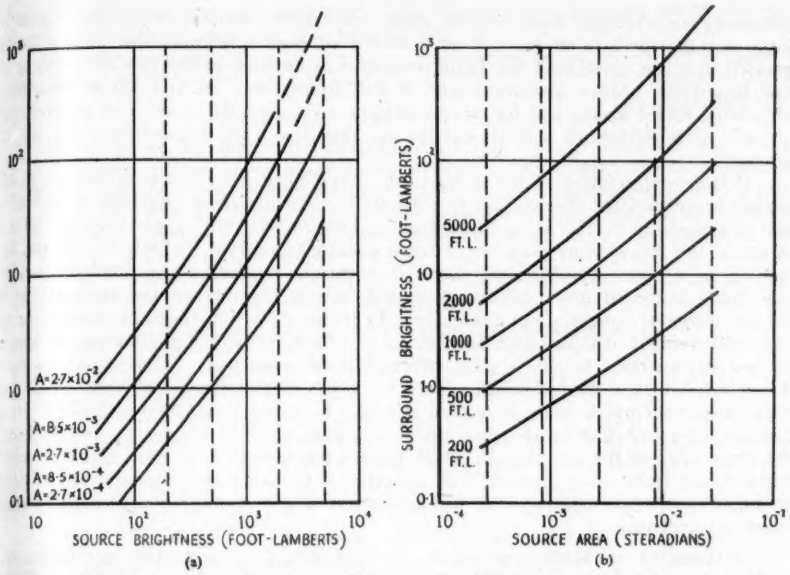


Fig. 7. Equal-glare curves for criterion C (just acceptable) showing effect of (a) change in brightness of source of given area, (b) change in area of source of given brightness.

ordinates, are probably S-shaped with characteristic threshold and saturation levels. The threshold brightness to give discomfort will be greater, the smaller the apparent area of the source. Similarly the saturation level beyond which glare will result whatever the surround brightness will be less, the greater the apparent source area.

The observations do not show whether there is any significant difference in the slopes of the straight-line portions of the curves for the different source areas. Of much greater importance is the fact that the saturation levels are approached in practice in the case of large sources (e.g., windows) of high brightness (3,000 foot-lamberts and over), the shoulder of the S-shaped equal-glare curves then applying and consequently

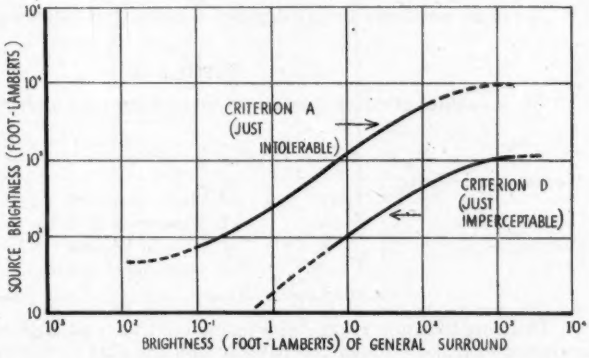

SOURCE BRIGHTNESS (FOOT-LAMBERTS)
CRITERION A (JUST INTOLERABLE)
CRITERION D (JUST IMPERCEPTABLE)
BRIGHTNESS (FOOT-LAMBERTS) OF GENERAL SURROUND

Fig. 8. Empirical curves derived from averaged observations showing probable form of equal-glare curves. (From data for source area 2.7×10^{-2} steradians).

producing an effective change in the slope. It can be deduced from this change of slope that an increase in the size of a source of high brightness will have a rather greater effect on glare than the same proportional increase in the size of a source of low brightness. More important still, it will follow that an increase in brightness of a large bright source will have a greater effect on glare than the same proportional increase in brightness of a small source, and this is, in fact, demonstrably the case in practice.

If this interpretation of the true nature of the equal-glare curves is correct, it will readily be appreciated that any simple formula such as that given originally by Holladay and subsequently by Harrison, Hopkinson and others, can only apply over the limited range of the straight-line portions of these equal-glare curves. Moon [19], in the discussion on a paper by Harrison, shows the inherent fallacy of any attempt to cover the whole range of glare conditions with a simple formula of the Holladay type. (Moon, however, offers a substitute formula which does not appear to overcome all the disadvantages of that which he criticises.) The S-shaped equal-glare curves appear to give explanations for most glare effects, but the assessment of glare on this basis is not offered as a final statement, because it is realised, from the work which has been done, that much more is needed in order to achieve this final statement. It is unlikely, however, that much more can be achieved until physiologists have advanced our knowledge of the mechanisms which govern the sensations of pain and discomfort which result from over-stimulation of the retina. It may then be possible to advance an hypothesis which embraces all the discomfort effects, and thus replace the present empirical approach.

Criticism of the Holladay formula on fundamental grounds does not necessarily apply if it is used solely as a help in design problems over a limited range of conditions, and provided it is not extrapolated beyond these conditions. It is the danger of such extrapolation that deters investigators from simplifying their data in this way for the benefit of designers. The data of the present study can be expressed by the Holladay formula in the following way:—

$$\text{Glare Constant} = \frac{B_s^{1.6}\,\omega^{0.8}}{B_b^{1.0}} \text{ over a very limited range}$$

where B_s is the brightness of the source in foot-lamberts,
ω is the apparent area of the source in steradians,
B_b is the general background brightness of the surroundings in foot-lamberts.

The glare constant calculated in this way has the following values:—

TABLE 2

Values of Glare Constant derived from the Experimental Data.

Glare Constant	Corresponding Criterion of Discomfort under conditions of No Visual Task
600	A. Just intolerable
150	B. Just uncomfortable
35	C. Just acceptable
8	D. Just imperceptible

This simplification is only approximately true, and is given solely to enable those interested to make a rough comparison with the data of earlier investigators, and also

because it is occasionally of assistance to be able to make a rough calculation of a glare effect without consulting the detailed data.

The formula applies to a glare source displaced by an angle of 10 deg. from the direction of view.

(b) Effect of Source Shape on Discomfort Glare

Six sources of different shape were studied. The areas of these sources were the same, but their proportions of length to height were different, such that at the extremes of shape there was a source whose length was 40 times its height, and a source whose height was 10 times its length. The angular subtense of their sides at the observer's eye, together with the sizes of equivalent sources viewed at a distance of 15 feet, are given in the following table:—

TABLE 3

Sizes of Light Source used in the Study of Source Shape.

Proportions Length : Height	Angular Subtense of Sides (Degrees)	Equivalent Size at 15 feet
1 : 10	1° × 9°	3 in. × 2 ft. 6 in.
1 : 2.5	2° × 4½°	6 in. × 1 ft. 3 in.
1 : 1	3° × 3°	9½ in. square
2.5 : 1	4½° × 2°	1 ft. 3 in. × 6 in.
10 : 1	9° × 1°	2 ft. 6 in. × 3 in.
40 : 1	18° × ½°	5 ft. 0 in. × 1½ in.

In all these observations the fixation point used to locate the observer's line of sight was at a fixed angular displacement of approximately 10 deg. vertically below the centroids of the different sources, these centroids all coinciding in position in the field of vision. As a consequence the fixation point was nearer the lower edge of some

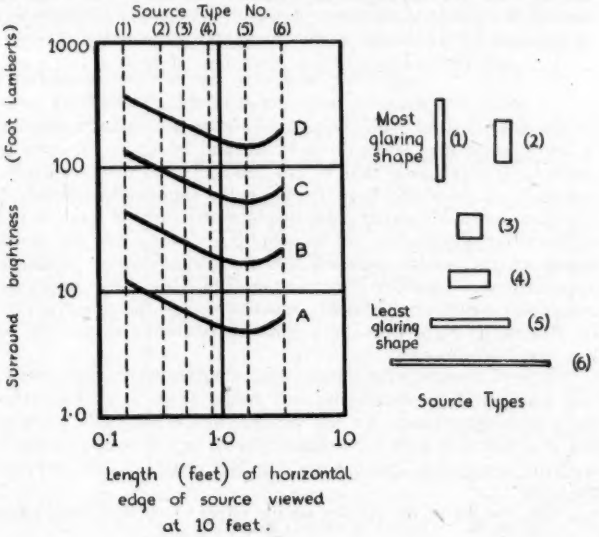


Fig. 9. Variation of surround brightness with shape of source to give four degrees of glare with source brightness of 3 candles per sq. in.

sources than others. This meant that the results would be influenced by any effect which the angular separation of the source from the direction of viewing might have. (See (c) below.)

It was found that, under the same conditions of source and surround brightness, a long source mounted horizontally is no more glaring than a square source, but that a long source mounted vertically causes a pronounced increase in glare.

This is illustrated by the equal-glare curves in Fig. 9, source type No. 5, with a length 10 times its height being the least glaring of the six shapes, and source type No. 1, with a height 10 times its length, being the most glaring.

Table 4 shows how the degree of glare from a typical source varies with the proportions of the source.

TABLE 4

Variation of Degree of Glare with Proportions of a Source of Brightness 3 Candles per sq. in. seen against a Surround of Brightness 20 foot-lamberts.

Type of Source		Degree of Glare	
No.	Proportions:—Length : Height		
(1)	1 : 10 (long source mounted vertically)	A/B	Pronouncedly uncomfortable
(2)	1 : 2.5	A/B	Very uncomfortable
(3)	1 : 1 (square source)	A/B	Uncomfortable
(4)	2.5 : 1	B	Just uncomfortable
(5)	10 : 1 (long source mounted horizontally)	B/C	Distracting but not uncomfortable
(6)	40 : 1	B	Just uncomfortable

These results suggest that, under conditions comparable with those of the experiment, a horizontally-mounted fluorescent lamp will be less glaring than the same source mounted vertically; they also suggest that a tall window exposed to the sky is more glaring than a long window of equal area and exposure, provided that the general environment brightnesses of the two types of window are the same.

(c) Effect of Source Position on Discomfort Glare

A study was made in some detail of the effect of the position of a source relative to the line of sight. Fixation points were provided at angular displacements between 4 deg. and 16 deg. vertically beneath and horizontally from the centroid of the glare source. It was found that within this range of displacements there was only a slight variation in glare and that there was no significant difference in glare between equal horizontal and vertical angular displacements of the fixation point. Studies were made of the effect of glare sources located up to and beyond the point at which a recognisable image of the source was registered by the eye. A slightly modified form of the apparatus was used for these studies (Fig. 10), cross checks being made between data obtained on both model arrangements. From the observations obtained, the variation of discomfort glare with the angular separation between the source and fixation point has been determined.

It is of interest that no significant difference in glare between equal small vertical and horizontal displacements was found (Fig. 11). This does not obviate the need for a correction factor for the location of the source in relation to working conditions, but it shows that such a correction factor is a function of the brightness pattern of the working conditions and not (to the first order) of the physiological characteristics of the eye.

The results of the studies on the effect of vertical displacements of the glare source

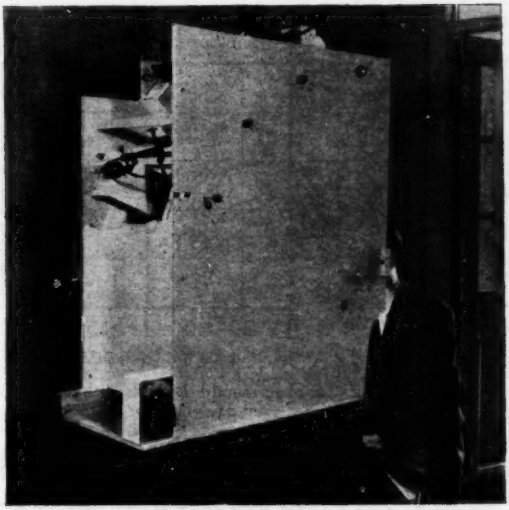


Fig. 10. Apparatus for the study of glare sources displaced from the direction of viewing.

are shown in Fig. 12, in which the surround brightnesses, which balance out the glare effect of a source of given brightness and area, are plotted against the displacement of the source from the direction of view.

The data can also be expressed in the form of Fig. 13, which shows directly the increase in the brightness of a source which can be tolerated if the source is displaced from the direction of view. This shows that, for each 10 deg. of displacement up to about 30 deg., the source can be about 1.3 times as bright for the same degree of glare, other conditions remaining constant. If the source is displaced by more than 30 deg., the glare effect is reduced by a far greater amount, so that, for example, a source displaced by 60 deg. can be 20 times as bright as one displaced by only 5 deg.,

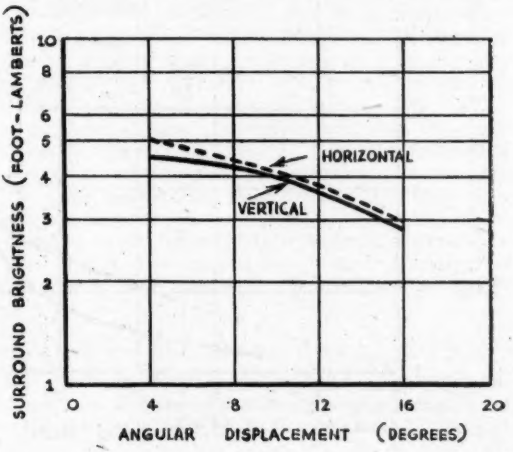


Fig. 11. Comparison between variations in glare due to horizontal and vertical displacements of fixation point from glare source.

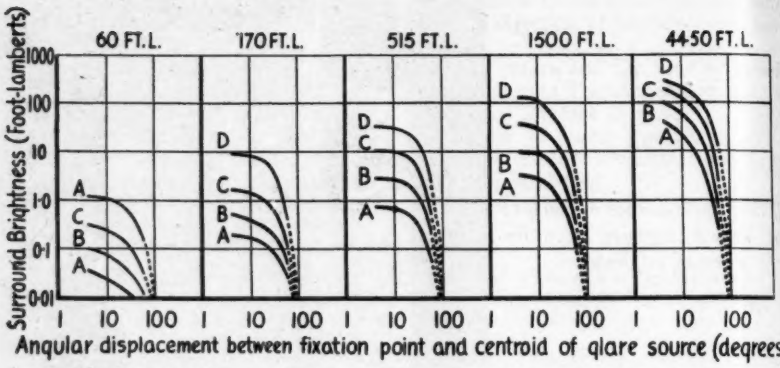


Fig. 12. Variation of surround brightness with angular displacement between fixation point and centroid of glare source to give four degrees of glare at each of five levels of source brightness.

for the same degree of glare. (This does not, however, take into account certain other effects, which will be discussed later.)

In Appendix I the data of Figs. 12 and 13 have been fitted to design formulæ of hyperbolic form.

The effects (on discomfort glare) of the displacement of the glare source from the direction of viewing can also be expressed in the form shown in Table 5.

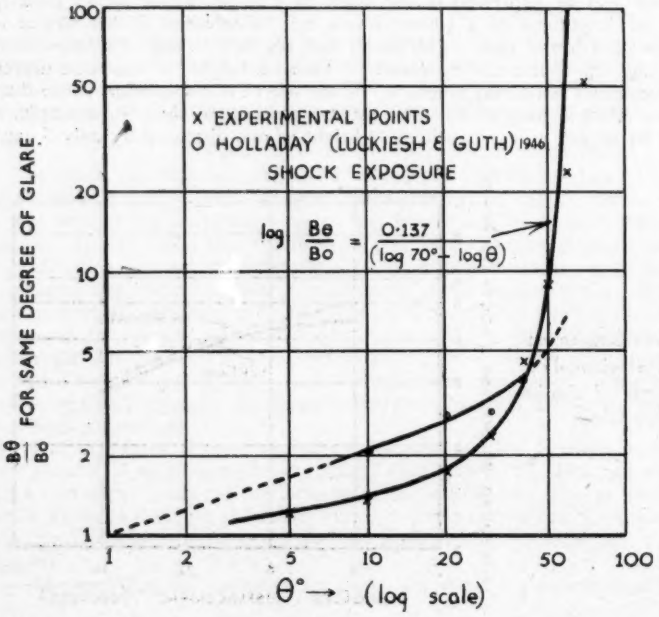


Fig. 13. Tolerable increase of glare source brightness due to displacement of source from direction of view.

TABLE 5

Effect of Displacement of Source on Discomfort Glare

Angle θ between Glare Source and Direction of Viewing	Mounting Height of Source (feet) at 20 feet distance (eye level 5 ft.)	Relative Brightness of Source for Constant Glare and Brightness of Background	Relative Brightness of Background for Constant Glare and Source Brightness	Approximate Assessment of Degree of Glare for Constant Source and Background Brightness
5°	7	0.8	1.2	A/B Uncomfortable
10°	8½	1.0	1.0	A/B Uncomfortable
15°	10½	1.14	0.8	B Just uncomfortable
20°	12	1.4	0.7	B Just uncomfortable
30°	16½	1.7	0.4	B/C Distracting but not uncomfortable
40°	22	3	0.2	B/C Almost acceptable
50°	—	7	0.1	C Just acceptable
60°	—	20	0.03	D Just imperceptible

The data for the above table were based on a source whose angular subtense at the eye is equivalent to that of a 14 in. opal globe at a distance of 20 feet. The source was assumed to have a brightness of 1.0 candles per sq. in., and to be seen in a general environment of 1.5 foot-lamberts. Eye level was assumed to be 5 feet.

Thus a source which gives rise to uncomfortable glare when seen at 10 deg. above the direction of viewing, will give hardly perceptible glare if removed beyond 50 deg. There will be only a small reduction in discomfort if it is removed by only 5 deg. to 15 deg. Similarly a source mounted at 12 feet (7 feet above eye level) can be about 1½ times as bright as a source mounted at 8 feet (3 feet above eye level) without any increase in discomfort, but *only* if the visual task involves a fixed direction of viewing. Alternatively, if the source brightness remains unchanged, the background brightness to a source mounted at 12 feet (20 deg.) need be only about three-quarters of that necessary for the same comfort conditions as those of a source mounted at 8½ feet (10 deg.).

It appears, however, much wiser to make no design use of formulae of the type developed in Appendix I. The advantage of small displacements of the source from the direction of viewing is relatively so insignificant, and the effect of large displacements (45 deg. and more) relatively so great, that the better method is to consider small displacements as affording no more than a useful factor of safety, and to consider large displacements as affecting a major reduction in direct discomfort.

The experimental results do not, however, give a complete picture of the effect of the displacement of the source from the direction of viewing. Observers found that a remote source, whilst giving no direct discomfort, could cause distraction or irritation, which could not be assessed on the same basis as the glare effect. This may be a psychological rather than a physiological phenomenon.

It is evident that, until more is known of the nature of these findings, the existence of glaring sources in any part of the field of view, even a remote part, is to be considered undesirable, and it is preferable to take additional effective steps to render such sources free from glare.

(d) Additive Nature of Glare Effects

A study was made of the glare effects produced by a number of sources simultaneously present in the field of view. In Hopkinson's street-lighting investigation it was found that with small sources the glare was additive, as demonstrated by the fact

that the surround brightness corresponding to a particular degree of glare when a number of sources was present in the field of view was the sum of the surround brightnesses necessary to produce the same degree of glare when each of the sources was present separately.

In the present investigation four equal sources of a size more comparable with those met with in interior lighting conditions were used, observations being made of the surround brightnesses necessary to give each of the four glare criteria with one, two, three and four sources in the field of view. Observers were also asked to express their subjective reactions to the addition of sources in this way.

In order to eliminate any effect due to fatigue, each observer made two sets of observations, the combinations of sources being viewed in different orders on each occasion. Furthermore, to eliminate any effect due to source size, observations were made using two sets of sources, the areas of one set being ten times those of the other. Similarly observations were made at five widely different levels of source brightness.

From all the observations obtained averages were determined of the surround brightnesses necessary to give the four degrees of glare at each of the five levels of source brightness when two or more of the sources were simultaneously exposed to the observer. Comparisons were made between these average values, and comparable values obtained with only a single source in the field of view.

The first comparison assumed that arithmetic additivity of the glare effects of sources applied, the average surround brightnesses for a single source being increased by factors of two, three or four to correspond to the number of sources it was assumed were being viewed. It was found that there was a significant difference between the two series of surround brightnesses, the values obtained experimentally by direct

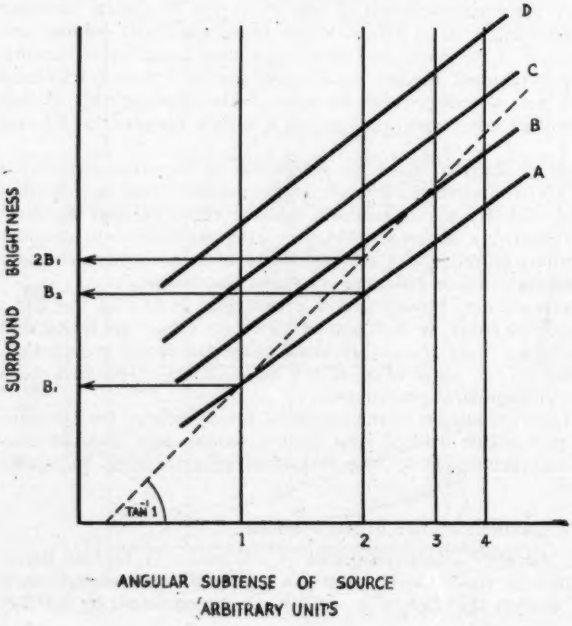


Fig. 14. Diagrammatic representation of relationship between increase in area of a source and corresponding increase in glare.

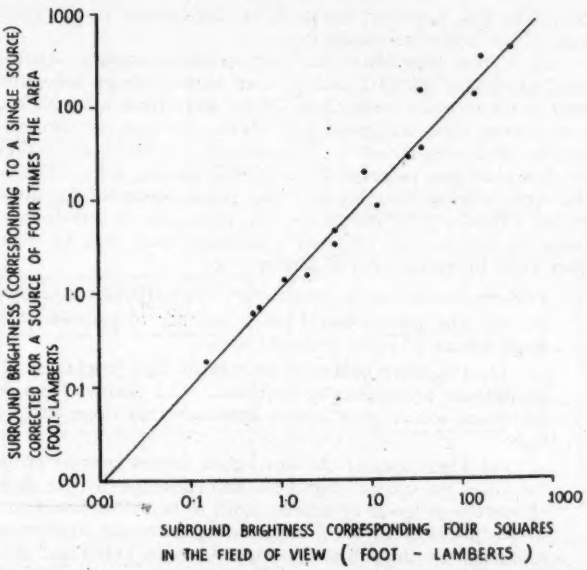


Fig. 15. Comparative surround brightnesses and associated regression line obtained from additive glare data.

observation on two or more sources being smaller than those computed from observations on a single source. This indicated that arithmetic additivity, such as was found in the street-lighting work, did not apply to these larger sources of lower brightness.

Two further comparisons employed the values obtained from the investigation of the influence of source area on glare (see Section IV(a)), in which it was found that a less than proportional increase in the surround brightness was necessary to compensate for a given increase in source area for constant degree of glare. (This follows from the formula derived in Section IV(a), and is illustrated by the experimental results of Fig. 7(b).)

In Fig. 14 the equal-glare curves derived from Section IV(a) are seen to have a slope less than unity. If a single source is considered to subtend one arbitrary unit of angular measure at the observer's eye, and the compensating surround brightness to give a just intolerable degree of glare is B_1 units of brightness, then a single source subtending 2 units of angular measure will require a compensating surround brightness of B_2 units to give the same degree of glare, where $B_2 < 2\ B_1$.

If arithmetic additivity had applied, two sources, each subtending 1 unit of angular measure, would require $2\ B_1$ units of surround brightness. This would imply that the glare from two such sources is greater than that from a single source of the same total area. The first comparison indicated that this was probably not so.

In the two further comparisons the average surround brightnesses for a single source were increased by factors corresponding to the total area of source present, the factors being obtained from the slopes of the equal-glare curves of Fig. 6.

One of these two comparisons used the actual slopes of individual curves. It was found that there was then no significant difference between the values of surround brightnesses obtained by the two methods. Fig. 15 shows the two series of surround brightnesses plotted one against the other and a regression line drawn through the points.

The other comparison employed the smoothed averages of the slopes of the equal-glare curves at each source brightness level. The correlation between the two series

of values was, however, not quite so satisfactory in this case, but closer than in the case of the arithmetic addition.

A further experiment was performed to confirm whether sources of the same total area were equally glaring when viewed under the same conditions. Observers were asked to make assessments of the glare from a simple rectangular source. These assessments were compared with those obtained on two other types of rectangular source, all having the same effective area. One source represented a window having six panes of glass separated by narrow glazing bars. The other source represented the same window area but with the panes separated by distances more nearly equal to the dimensions of the panes. In each case it was found that within the average limits of accuracy of observer's readings, there was no significant difference in the glare from the three types of source.

The conclusions to be drawn from this particular investigation are :—

(1) The glare effect from a number of sources is the same as that from a single source of equal apparent area.

(2) The glare effects of sources of high brightness (15,000 foot-lamberts and greater) are arithmetically additive. This follows from the fact that the surround brightness/source area curves approach unit slope when the source brightness is high.

(3) The slopes of the equal-glare curves become progressively less than unity, the lower the source brightness, and consequently the glare produced by a number of sources of lower brightness tends to be rather less than would be expected from simple addition of the compensating surround brightnesses. This tendency was confirmed by the subjective impressions of individual observers.

(4) The additive nature of glare can be expressed simply by an equation of the form :—

$$B_n = B_1 \times n^x$$

where B_n is the surround brightness necessary to produce a certain degree of glare with n equal sources in the field of view.

B_1 is the surround brightness to produce the same glare conditions with only one source.

and x is the slope of the surround brightness/source size equal-glare curves, having values less than unity for low source brightnesses and tending towards unity with increasing source brightness.

This formula would need to be modified, should the sources be of different areas and/or of different brightnesses.

It is known that certain methods of arrangement of the sources in the field of view cause individual observers to react aesthetically against them. This point has not, however, been investigated. Furthermore, it has been assumed that the individual sources are not so widely dispersed as to introduce effects due to their angular separation from the fixation area.

In applying these results to the design of a lighting installation it is probably more convenient to assume that arithmetic additivity applies even with sources of low brightness. This would automatically introduce a factor of safety to the calculated brightnesses.

It will be realised that in a study of such effects, a considerable number of observers, each making a large number of observations, is very necessary. These were not available in the present case, but the observations which were obtained when analysed by suitable tests for significance, led to the above conclusions.

(e) Effect of Contrast Grading between a Source and its Surround

A study was made of the influence which the brightness of the immediate surround

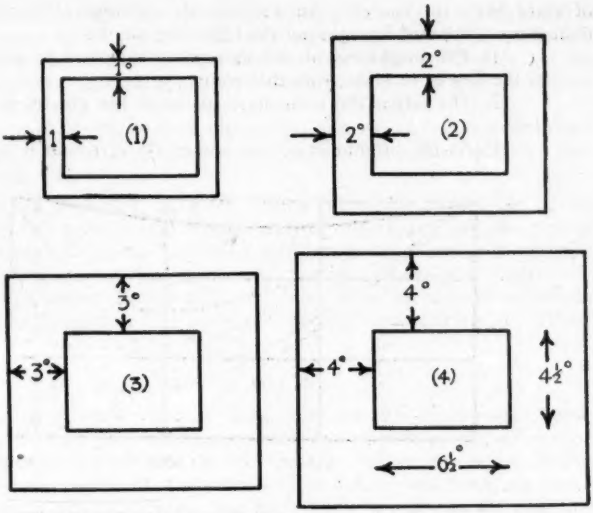


Fig. 16. Angles subtended at the observer's eye by a rectangular source and four widths of immediate surround used in concrete grading investigation.

of a source has on the degree of glare from the source. A single rectangular aperture, representing the proportions of a window, was used, the brightness of its immediate surround being capable of variation either in conjunction with or independently of that of its general surround. Observations were obtained with four widths of immediate surround, the angles which the rectangular source and the surrounds subtended at the observer's eye being shown in Fig. 16.

The effect of the immediate surround on the appraisal of discomfort glare was found to be complex. The two upper sets of curves in Fig. 17 were obtained by a typical observer and show how the discomfort due to glare from a source varies with increasing brightness of the immediate surround.

For each of the two source brightnesses illustrated (170 and 515 foot-lamberts) the conditions were first set so that with both the immediate and general surrounds of equal brightness, a just intolerable degree of glare was present. An increase in the ratio of immediate to general surround brightness, the general surround brightness remaining constant, is seen to first reduce the glare by assisting the local adaptation of the eye to balance out the effect of the source. (Thus, with a source brightness of 170 foot-lamberts and an immediate surround subtending 4 deg. at the eye, it was found possible to reduce the glare to an almost imperceptible degree.) A further increase in the ratio of the surround brightnesses, however, causes the immediate surround to become too bright, this surround itself then constituting an additional glare source, with consequent increase in discomfort. This is illustrated by the change in slope of the curves. In each case the vertical dashed line represents the brightness of the source expressed as a ratio of that of the general surround. Where the glare curves cross these dashed lines the brightness of the immediate surround has been increased beyond that of the source.

The lowest set of curves shows that with a source brightness of 170 foot-lamberts and the surround brightnesses equal and set for just imperceptible glare, an increase in the immediate surround brightness causes an increase in discomfort glare up to and beyond the just acceptable criterion.

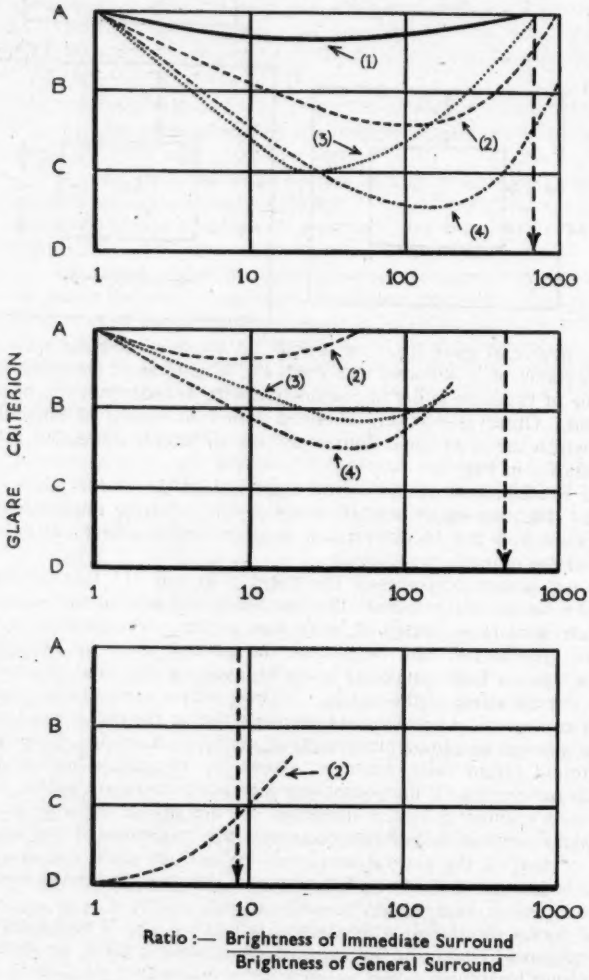
The width of the immediate surround is seen to have an influence on the degree

of glare from the source. An analysis of a considerably greater number of curves than those illustrated brought out the following points:—

(1) The brightness of the immediate surround to a source has an influence on the degree of glare from that source.

(2) The larger the immediate surround the greater is the influence it has on glare.

(3) As the brightness of the immediate surround is increased beyond that of



(a) Source brightness 170 ft.l. General surround brightness corresponding to glare criterion A.

(b) Source brightness 515 ft.l. General surround brightness corresponding to glare criterion A.

(c) Source brightness 170 ft.l. General surround brightness corresponding to glare criterion D.

Fig. 17. Variations in glare from a source due to changes in the brightness of immediate surrounds of different widths.

the general surround the glare is first reduced until a minimum level is reached. The degree of improvement of the glare conditions depends on the width of the surround, the brightness of the glare source and the initial glare criterion. If the source is of low brightness and the initial glare was considerable, a major improvement can be effected.

If, however, there is originally little discomfort present, an increase in brightness of the immediate surround will probably have little effect, and in fact it may make the glare worse (Fig. 17 (c)).

(4) The maximum reduction in glare occurs when the brightness of the immediate surround lies between the brightnesses of the source and the general surround. The magnitude of the reduction depends on the source brightness, the original degree of glare and the size of the immediate surround. Indications are that greater brightnesses can be tolerated from wide immediate surrounds, with consequent larger reductions in glare, but further observations are needed before this can be definitely confirmed.

(V) Discussion of Results

The studies reported in the paper were directed more towards an extended knowledge of the relationship between the various physical factors which govern discomfort from glare, rather than towards prescribing the precise values of these factors associated with any specific degree of discomfort. The results are therefore not a substitute for experience of lighting practice, but serve more to assist in the quantitative interpretation of this experience. The studies illustrate the complexity of the problem of discomfort glare where sources are large and therefore themselves influence the general adaptation of the eye. The more simple system formulated from the results in street-lighting conditions no longer applies nor can a simple expression of the type suggested by Holladay and employed by Harrison and Meaker ([24]) be used to cover all the effects of large glare sources. This is particularly true in the case of windows.

The following conclusions result from the studies:—

(a) Distinctions can be made between the factors which influence discomfort and disability glare. These are:—

(i) Discomfort is confirmed as a function of source brightness, whereas it is known that disability is independent of the brightness of the source.

(ii) The effect on discomfort of small displacements of the source from the direction of view is relatively small in comparison with the effect on disability.

Consequently, conditions which govern design to counteract disability will not necessarily counteract discomfort. If this gives rise to any design conflict it is necessary to decide whether discomfort or disability is the major glare problem. In the case of lighted streets it was known that discomfort was far more significant than disability and so new designs were based on this fact; thus source brightnesses rather than source intensities were reduced in order to counteract discomfort effects.

In buildings disability glare is often a major problem. The most effective methods of reducing disability glare are associated with reductions in the source intensities and with the removal of the sources from the direct field of view. These also reduce discomfort, so that no design conflict may arise.

It can be clearly and simply demonstrated experimentally that the laws which govern disability from glare are not the same as those which govern discomfort. At a relatively low environment brightness level a large source, such as a window, of low brightness but high intensity ($I = B \times A$) can cause considerable disability, a veil or

"entoptic halo" seen around the window preventing any detail from being distinguished. Yet no discomfort results, since the eye can easily adapt itself to the low sky brightness.

On the other hand, under conditions such as those in a room artificially lighted to the order of 100 lumens/sq. ft., a bare lamp may cause no disability, because the veiling effect has no appreciable influence on the brightness difference threshold (i.e. on the ability to see contrasts). The high brightness of the bare lamp will, however, cause considerable discomfort.

(b) One of the most significant of the results is the effect of a change of brightness of large sources. It is shown that an increase in brightness of a large window, accompanied by only a proportional change in brightness of the general environment, causes a noticeable increase in discomfort. In other words, any increase in window brightness must be accompanied by a more than proportional increase in the brightness of the environment if the discomfort is not to increase. The greater the apparent area of the window the more must the environment brightness increase. Conversely it follows that a small reduction in the brightness of a large window is beneficial in reducing glare by a more than proportional amount. Both these effects have been strikingly demonstrated by field studies as well as experimental model studies. For example, a change of only 10 per cent. in the brightness of a large side window in a school room made a noticeable difference to the discomfort, and a change of up to 50 per cent. made a major difference (for example, from merely uncomfortable glare to intolerable glare). It was noted that a coating of dirt on such a large window made a noticeable reduction in sky glare although it reduced the window brightness by only 15 per cent.

(c) A source of low brightness (below 500 foot-lamberts) can be increased in area, and thus its intensity and the illumination it produces can be increased, with relatively little effect on the discomfort glare. On the other hand an increase in area of a source of high brightness (above 2,000 foot-lamberts) has a greater effect on the discomfort. These facts lead to various developments in building design. For example, they have led to the realisation of the need for properly designed blinds, louvres or obscuring devices for controlling the window brightness in classrooms with large windows. They have also demonstrated the value of such large windows in winter when skies are of low brightness, in that good illumination free from glare results.

(d) It has been clearly shown that a small angular displacement of the glare source from the direction of view has much less influence on discomfort and distraction than on the direct disability effect of the glare source. (This has also been shown in the case of the street-lighting work.) On the other hand, large displacements of the glare source produce a very great reduction in discomfort.

A knowledge of these factors serves, for example, to guide the placing of factory tasks in relation to windows and for positioning school lighting fittings in relation to the teaching area.

(e) It is safe to assert that, to the first order, the glare effects of a number of sources are additive (but see Section IV (d)).

(f) The experimental results show that glare is increased if the illumination conditions in a room are improved by raising the intensity of the existing sources merely by an increase of their intrinsic brightness. Although the brightness of the general environment will certainly be raised by such an increase of the brightness of the sources, the sharp dependence of the discomfort effect on source brightness means that the glare effect will not be balanced out. Consequently improved illumination levels must not be provided merely by increasing the brightness of the sources of an existing installation. The advantage in visual efficiency which may be gained by the

improved illumination may in effect be balanced out for long-period working by the increased discomfort which results from the added glare.

(g) The studies confirm that long sources if mounted vertically will give rather more discomfort than the same sources mounted horizontally. A single long source such as a fluorescent lamp is no more glaring than a compact rectangular or square source of the same surface brightness. This does not, however, take into account the distraction which arises from an aggressive pattern of formally arranged long sources, a factor which has not been studied.

(h) To a limited extent the glare from a source or a window can be reduced by increasing the brightness of the immediate surround, but taking care that the increase is not so great as to constitute a secondary source of discomfort.

Thus:—

(i) For sources of low brightness (less than 500 foot-lamberts) the effect of raising the brightness of the immediate surround can definitely be beneficial in reducing glare, especially if the surround has an area about four to ten times that of the source.

(ii) For sources of high brightness (greater than 500 foot-lamberts) the effect of raising the brightness of the immediate surround is not so certain. It is possible that at these higher brightnesses the eye may be saturated by the integrated intensities of the source and surround.

(iii) Any influence which the immediate surround may have on glare seems to be more marked when the degree of glare from the source is high. Low degrees of glare do not seem to be assisted by grading the surround brightness.

It is not certain how much of the benefit which results from grading the source is due to a direct reduction in discomfort and how much is due to the reduction of the irritation caused by the awareness of the entoptic halo. The data obtained are sufficient to show that for some observers at least, real advantage is achieved by careful gradation of the source into its surroundings. It is interesting that a simple school lighting fitting designed from a consideration of these experimental studies has confirmed this advantage.

(VI) Application to Design Problems

The main purpose of the paper has been to report the results of the experimental studies. Architects and lighting engineers will eventually need to have the conclusions arrived at from the studies condensed into a form suitable for direct application to lighting design. Such a condensation is one which presents more problems to the investigator than to any other person. He is more aware of the limitations of his experimental conditions, and also he is equally keen to include information which may appear to be of fundamental significance, but which may be of relatively little use in design.

The present studies reveal the complexity of the glare problem, such that any form of condensation must necessarily be incomplete and misleading if used without a knowledge of the subject as a whole. However, some useful generalisations are possible at this stage. These may be revised or supplemented later when more experience has been gained of their application to full-scale problems of lighting design.

(a) Relationship Between Source and Environment Brightnesses and Degree of Glare

The experimental evidence shows that, under the conditions of the experiment, much of present-day artificial lighting equipment results in some discomfort glare. For example an installation designed to give a general illumination on the working plane

of 10 lumens/sq. ft. will have a general environmental brightness of the order of 1—5 foot-lamberts (depending on the utilisation factor of the fittings, the reflection characteristics of the walls, ceilings, etc.); such a background brightness demands that fittings of the usual size ($\omega = 10^{-3}$ steradians or thereabouts) should have a brightness of the order of 100—500 foot-lamberts (0.2—1.0 candles/sq. in.) if the glare is to be acceptable. Very few fittings common in installations of this order of illumination have a brightness as low as this. The Illuminating Engineering Society's Code of Lighting Practice recommends values of the order of 2.5—5 candles/sq. in. as maxima for such conditions. The present studies indicate that such values lead to glare on the borderline of discomfort (criterion B). These values are, therefore, definitely maxima, as the Code indicates, and should on no account be exceeded.

Tables 6 and 7 give values of source brightness and general environment brightness for an installation fairly typical of present practice. The two right-hand columns of Table 6 give the probable general background brightnesses in a room 12 feet high with light walls and ceiling, and with one light fitting to each 100 sq. ft. of floor area.

TABLE 6

Relationship between Brightness of Source and Brightness of the General Environment for Different Degrees of Discomfort Glare, for Three Sources Mounted 10 Deg. above the Line of View and Subtending Angles Equivalent to a 14-in. Diameter Opal Globe when seen at 20 Feet

Brightness of Source (candles/sq. in.)	Surround Brightness (foot-lamberts) for :—				Probable room brightness (foot-lamberts)	
	A Just Intolerable Glare	B Just Uncomfortable Glare	C Just Acceptable Glare	D Just Imperceptible Glare	Walls	Ceiling
0.5	0.2	0.9	4.2	18	1	2.5
1.0	0.6	2.3	11	43	2	5
2.0	1.7	6.0	31	120	4	10
5.0	5.8	21	120	430	10	25
10.0	15	56	340	1200	20	50

TABLE 7

Ratios of Brightness of Source to Brightness of Environment for Different Degrees of Discomfort Glare (Derived from Table 6)

Brightness of Source (candles/sq. in.)	Ratio of Source Brightness/Surround Brightness for :—			
	A Just Intolerable Glare	B Just Uncomfortable Glare	C Just Acceptable Glare	D Just Imperceptible Glare
0.5	1,130	251	54	13
1.0	755	197	41	10
2.0	532	151	29	7.5
5.0	389	108	19	5.2
10.0	302	81	13	3.8

It is of interest to compare the probable brightnesses in the installation considered in Table 6 with the necessary values of surround brightness for the specified degrees of glare. Thus an installation with fittings of brightness two candles/sq. in. (i.e., 14-in.

opal globes lamped with 200-watt lamps) will be uncomfortably glaring unless the surroundings are brighter than six foot-lamberts. In fact, such an installation will have walls of rather lower brightness, and a ceiling of higher brightness, so that the glare will therefore be expected to be on the borderline of discomfort. This is, in fact, a fairly generally held opinion, even though the data of Table 6 are based upon the averaged determinations of only six observers.

Similarly, the limiting values of source brightness specified by the I.E.S. Code (2.5 candles/sq. in. in some circumstances and 5 candles/sq. in. in others) are seen to be on the borderline of definite discomfort. This is pointed out in the Code, where these values are given as maxima for the permissible source brightness. The results, therefore, agree with the Code in this respect.

Tables 6 and 7 enable a rough appraisal to be made of the desirable levels of brightness for a restricted range of conditions. For a wider range of conditions, the calculation of Appendix III may be used, or, preferably, reference back to the experimental data should be made.

Tables applicable to natural lighting conditions are less useful, since the major constants of the installation (e.g., the brightness of the sky seen through the window) are not under control. The data show clearly, however, that some discomfort results from the direct view of the sky even when the sky brightness is as low as 2,000 foot-lamberts, and the surroundings in the room are as bright as 100 foot-lamberts. This has been confirmed amply by field studies.

(b) Methods of Reducing Glare

In all conditions, both of natural and artificial lighting, where discomfort from glare exists, some reduction of the amount of discomfort is usually possible. Neglecting for the moment the effects of change of position of the sources, the most fruitful means of reducing glare are:—

(1) The sources can be screened without reducing the brightness of the general surroundings. If this can be done, a reduction of source brightness of 2.5:1 made in this way will reduce discomfort by one whole criterion, i.e., from B (just uncomfortable) to C (just acceptable).

The greater the size of the source the less the reduction in source brightness necessary to reduce discomfort by the same amount. For example, the reduction in brightness of a large window from 5,000 foot-lamberts to 3,300 foot-lamberts (i.e., about 30 per cent.) will produce the same degree of reduction in discomfort, i.e., from B (just uncomfortable) to C (just acceptable).

(2) If the illumination in the room is already more than adequate (e.g., in a room with large windows, on a bright day) the brightness of the surroundings may be reduced in proportion to the reduction of the brightness of the sources, for example, by the use of absorbing glass or translucent curtains in the window. In a room with large windows, such a proportional reduction of the order of 3:1 will reduce discomfort by one criterion. For example, the view of a large area of sky (white cloud), of brightness about 5,000 foot-lamberts, seen in surroundings of 500 foot-lamberts, causes uncomfortable glare. If the window brightness is reduced to about 1,500 foot-lamberts (by a translucent curtain, for example), the glare will be acceptable, even though the room brightness is now reduced to about 150 foot-lamberts. There is still ample illumination for good vision, and the discomfort caused by glare has been removed.

(3) It is often not possible to afford a reduction in the illumination level in the room. In this case it follows that to retain the same illumination level from sources of reduced brightness either the number of sources or their effective area must be increased. A reduction in glare by one whole criterion of discomfort will be achieved if the sources are reduced in brightness by a factor of 6:1 with a reciprocal increase in the number of sources or their effective area.

(4) The general background brightness can be increased (e.g., by attention to

wall finishes, by better redirection of light from the sources, or by adding light from sources not visible to the observer). An increase of background brightness of 4:1 will reduce discomfort by one whole criterion.

Other less useful methods of glare reduction are:—

By raising the sources as far from the general direction of viewing as possible. It will, however, be necessary to raise the sources beyond 45 deg. to the direction of viewing if the discomfort is to be reduced by one whole criterion, and this presupposes that the visual task dictates a constant direction of viewing.

By increasing the brightness of the immediate surroundings to the sources (a substantial increase, of the order of 20:1 or 100:1 may be necessary—see Section 5 (h)). In the design of lighting units, the gradation of the brightness of the light source into that of the general surroundings can often be achieved by the careful use of partially diffusing translucent materials. Recent developments in polymerised ethylene products have resulted in some materials which have suitable optical properties.

(VII) Conclusion

The studies reported in the paper are directed towards a better understanding of the basic factors of discomfort glare rather than of the general systematisation of these factors. If required, the results obtained from the studies can, however, be applied directly to such a Code of Practice. The interest in the glare factor system of Harrison and Meaker in the United States may suggest that a codification is of value. General experience allied to the present studies suggests, however, that such a system may possibly lead to some misjudgment in the interpretation put on a "glare factor" obtained from a calculation. The essential danger is that if a number (that is, a "glare factor") is given to an assessment of a subjective effect, it will naturally be interpreted arithmetically, so that an installation with a glare factor of 100 will be considered twice as glaring as one with a glare factor of 50. In fact, such an interpretation is meaningless. Harrison and Meaker are very careful to point this out. Nevertheless, the authors' preference is for a better understanding of the interrelationship of the relevant physical factors in a form suitable for direct application to design, rather than for a simplified, but necessarily only partly accurate, formulation of the data.

This investigation is part of the experimental lighting programme of the Building Research Station of the Department of Scientific and Industrial Research, and is published by permission of the Director of Building Research. The authors gratefully acknowledge the unflagging co-operation of their colleagues who undertook the observations, and especially the assistance of Mr. J. Longmore, who was responsible for much of the experimental work.

APPENDIX I

Formulae Relating the Effect of Source Position on Discomfort Glare

The curves of Fig. 12 show the surround brightnesses, which balance out the glare effect of a source of given brightness and area, plotted against the displacement of the source from the direction of view.

The form of the curves does not permit any simple formula of the Holladay type:—

$$B_\theta = B_o \frac{1}{\theta^n}$$

to be employed as a useful expression of the data for design purposes. The data will, however, fit an expression of hyperbolic form:—

$$(\log \theta_L - \log \theta)\ (\log B_o - \log B_\theta) = \text{constant } K$$

where θ_L is the value of θ (approx. 70 deg.—90 deg.) which represents the limit of the field of vision under the experimental conditions, and B_0 is the asymptotic value of the surround brightness corresponding to the glare effect of a source in the direction of view.

The same values of θ_L, B_0 and K will not satisfy all the experimental data. For design purposes, however, the following values are reasonably close over the range θ = 4 deg. — 60 deg.:—

$$\theta_L = 70 \text{ deg.}$$
$$K = 0.18$$
$$\log_{10} B_0 = \log_{10} B_{10} + 0.18$$

where B_{10} is the value of surround brightness with which the source gives the required degree of glare, when displaced from the direction of viewing by θ = 10 deg. (B_0 is given in terms of B_{10} since it is impracticable to assess B_0 experimentally, whereas B_{10} can be readily assessed).

There is, of course, no fundamental value in the hyperbolic expression for the effect of the displacement of the glare source. It serves merely as a convenient method of calculating this effect.

In Fig. 13 is shown the increase in the brightness of a source which can be tolerated if the source is displaced from the direction of view.

The values from which this figure was derived can, if required, be fitted to a number of formulae, including the hyperbolic relationship:—

$$\log_{10} \frac{\beta\theta}{\beta_o} = \frac{k}{(\log_{10} \theta_L - \log_{10} \theta)}$$

where θ_L' is the angular displacement of the source beyond which no sensation of glare is experienced, and $\frac{\beta\theta}{\beta_o}$ is the ratio of the acceptable brightness of the *source* at a displacement θ deg. to the brightness of the source for the same degree of glare when viewed directly. The relationship gives $\frac{\beta\theta}{\beta_o} = 1$ when $\theta = 0$.

Values of k and θ_L which fit the data over the range θ = 5 deg. to θ = 50 deg. are:—

$$k = 0.137$$
$$\theta_L = 70^\circ \quad (\log_{10} \theta_L = 1.85).$$

APPENDIX II.

Comparison With Previous Studies

Comparison with previous studies is difficult, chiefly because it is not easy to link the descriptions of "comfort" and "discomfort" in some of these studies, with the criteria of discomfort used for the present investigations.

Holladay, who described his degrees of comfort with unusual precision, confined his studies to the "shock effect" of an observer adapted to one brightness suddenly encountering the higher brightness of a glare source. His work is not, therefore,

comparable with the studies reported in this paper. This is unfortunate, as his work was probably as carefully conducted as any which has been undertaken.

Holladay gives a formula for calculating the glare effect, as follows:—

Glare constant = log B + 0.25 log Q − 0.3 log F, which can be restated in the terms of the present studies as:—

$$\text{Glare constant} = \frac{B_s\,\omega^{0.25}}{B_b^{\,0.3}}$$ where B_s = source brightness
B_b = surround brightness
ω = apparent area of source.

The glare constant can, of course, be expressed in a form convenient for comparison, thus :—

$$\text{Glare constant} = \frac{B_s^{3.3}\,\omega^{0.83}}{B_b^{1.0}}$$

the exponent of the surround brightness B_b being adjusted to 1.0 as in the formula of Section IV(a). It will be seen that, whilst the exponent of ω then agrees with that derived from the averaged values of the present studies, the exponent of B_s is 3.3 instead of 1.6. This difference in the exponent of B_s is likely to be due to the difference between the effect of " shock " exposure and constant exposure of the glare source.

Harrison's restatement of Holladay's formula, which is based on extensive experience of lighting design, is as follows:—

$$\text{Glare constant} = \frac{B_s^{2}\,\omega}{B_b^{0.6}}$$

or, adjusting the exponent of B_b to be equal to 1.0:—

$$\text{Glare constant} = \frac{B_s^{3.3}\,\omega^{1.7}}{B_b}$$

Harrison thus attributes a greater influence to the area of the source than the present studies would support, whilst retaining the high exponent of the source brightness.

Moon, in his criticism of Harrison's work, prefers another formula :—

$$\frac{B_s}{B_b} = \frac{(B_s/B_b)\,\alpha}{\omega} \quad (0.00874 + \sqrt{10})^2$$

where

$(B_s/B_b)\,\alpha$ is the " allowable " (comfortable) ratio of source brightness to adaptation brightness for a very large source. Moon's formula, however, indicates that there is no upper limit to the allowable source brightness provided the adaptation brightness is sufficiently high. It is, however, well known that the eye cannot adapt to brightnesses much above 10^4 foot-lamberts. Moon's formula therefore cannot be accepted as a general expression for the discomfort effects of glare, since it suffers from disadvantages equally as serious as those of Holladay's formula.

It is of interest, however, that over a limited range of brightnesses of surround and source, the data given by Moon (derived indirectly from Holladay) are in reasonable agreement with the corresponding equal-glare curve for criterion C (just acceptable) for a large source (2.7×10^{-2} steradians) derived from the present data. The agreement with the data for a smaller source (2.7×10^{-4} steradians) is, however, poor for the criterion C curve, but more satisfactory in this case for the criterion D curve. It is

not known whether Moon's "allowable" glare level corresponds to criterion C (just acceptable glare) or criterion D (just imperceptible glare).

Vermeulen and de Boer [25] indicate that their data can be expressed, with reservations on extrapolation, by the formula :—

$$B_s = C \frac{B_b^{0.6}}{\omega^{0.3}}$$

$$\text{or glare constant} = \frac{B_s^{1.7}\ \omega^{0.5}}{B_b}$$

where the exponent of B_b has been raised to 1.0.

These values of the exponents agree closely with those of the present studies. Vermeulen and de Boer do not, unfortunately, define their criterion of discomfort sufficiently closely to enable a detailed comparison to be made with their data. It follows, however, that by choice of suitable values for the glare constants to correlate with the four criteria of discomfort specified in Section III above, good agreement between the two sets of data will result.

The effect of the angle between the direction of the glare source and the direction of viewing has been studied by some of the above investigators. Holladay's original studies did not embrace this effect in relation to discomfort, but Harrison has taken the exponent derived by Holladay from his studies on the disability effects of glare. As Parsons [20] points out in the discussion on Harrison's paper, there is no justification for this except on the grounds of expediency. Harrison and Meaker subsequently modify this exponent by giving a table of "location coefficients" which are based on more recent work of Holladay. (Moon does not give any weight to the effect of the displacement of the glare source.) Luckiesh and Guth [22], reporting and summarising this more recent work of Holladay, give data which fit into a formula :—

$$\frac{B_\theta}{B_c} = \frac{\theta^{0.8}}{\text{Cos}\,\theta}$$

where θ is the displacement angle and B_θ, B_c, are respectively the tolerable brightnesses at the displaced point and the fixation point.

This formula, being again based on the "shock effect," is not directly comparable with studies of the effects of continuously exposed sources. Fig. 13 illustrates Holladay's data on the same relative scale as the data for criterion C (just acceptable) from Fig. 12. It is seen that Holladay's figures for the "shock effect" and those of the present study show only a general agreement. Otherwise there is little detailed measure of agreement, and, in fact, this would not be expected since the experimental conditions were so different. Luckiesh and Guth note that Holladay's results do not apply to the conditions of continuous exposure of the glare source met with in practice, and offer the value of a factor of safety that might be used. The present studies suggest that, as might be expected, the difference between the "shock" and the "continuous exposure" conditions results in distinct relationships rather than a factor of safety to be applied to either.

The results given by Hopkinson for street-lighting conditions cover a range of brightness and source area outside the range of the present studies. It is not, therefore, possible to make a direct comparison between the two sets of experimental findings. In addition, the earlier data were derived from an experiment which involved a simple visual task, whereas the present studies, in the main, did not. It is, however, of interest that the findings of the two experiments are consistent one with the other. The Holladay-type formula averaged from the earlier data was :—

$$\text{Glare constant} = \frac{B_s^{1.3}\ \omega^{1.0}}{B_b^{1.0}},$$

for conditions of high source brightness (B_s) and small apparent area of source (ω)

whilst for the present study it is given as :—

$$\text{Glare constant} = \frac{B_s^{1.6}\,\omega^{0.8}}{B_b^{1.0}},$$ for conditions of lower source brightness (B_s) and larger area (ω).

The experimental results of both studies support a higher value of the exponent of B_s for large values of ω, and a lower value of the exponent of ω for lower values of B_s (See Figs. 5 and 6). Either formula can, in fact, with a suitable adjustment of the values of the glare constant, be applied to the results of either study under the most nearly comparable conditions of source brightness and area. Thus whilst the previous studies did not lead to the same values of the exponents of the Holladay formula as does the recent work, the observations themselves agree. In fact, the exponents of the Holladay formula over any limited range will necessarily differ, as was discussed under Section IV(a) above. This is a necessary limitation of an empirical formula which is not based on an all-embracing hypothesis.

These various comparisons with other work are given in some detail because in the study of a factor such as the discomfort due to glare, a large measure of uncertainty necessarily must be accepted. The use of the multiple-criterion technique is believed to have materially reduced this uncertainty; this belief is supported by the measure of agreement between the two studies in which this technique was employed. These studies were separated by a period of ten years, and were undertaken by different teams of observers.

APPENDIX III.

Glare Calculations

It is often considered desirable to be able to calculate the degree of glare in an existing or proposed lighting installation, or to specify the modifications necessary to such an installation to meet a required standard of maximum glare.

Discomfort arising from glare is, as has been discussed under Section II, a subjective sensation, and hence it is not possible to put any sort of measure upon it. An approximate assessment of the degree of glare in a building can, however, usefully be obtained by employing the formula of Section IV(a). It must, however, be realised that this can only be a rough guide, and should never be used as a form of specification or recommendation. Such recommendations should always be in terms of the physical constants of the lighting of the building.

The procedure is to calculate the value of the " glare constant " for the installation, and to compare the calculated value with those values appropriate to each of the four criteria of glare enumerated in Table 2. In this way the degree of discomfort likely to be experienced in the installation can be found in terms of these four criteria.

The design formula derived from the experimental data is as follows:—

$$\text{Glare constant} = \frac{B_s^{1.6}\,\omega^{0.8}}{B_b^{1.0}}$$ (see Section IV(a)).

where B_s = brightness of source (foot-lamberts).
ω = apparent area of source (steradians).
B_b = general background brightness (foot-lamberts).

This formula applies to sources located at 10 deg. from the direction of viewing.

Discomfort is reduced by displacing the sources from the direction of viewing (see Section IV(c)). The modification to the above formula to give the permissible allowance for such displacements is discussed in Appendix I. This modification should only be used if the nature of the visual task demands a fixed and constant direction

of viewing. Otherwise it is preferable to neglect the effects of displacements up to 50 deg., such advantages as accrue from small displacements being considered to be in the nature of a factor of safety. On the other hand, sources displaced beyond 50 deg. will cause little direct physiological discomfort, and their glare effects can therefore be ignored. (It is, however, advisable to remember that some people find that sources displaced by 50 deg. and more from the general line of sight are both distracting and irritating from aesthetic rather than physiological considerations.)

Since the glare constant is not a precision quantity, the calculations which follow have not included the allowances for the effect of displacement of the sources. If required, detailed tables of "location coefficients" can be readily prepared from the figures given in Section IV(c) and from Appendix I.

By use of the above formula values of the glare constant can be found for each source in the field of view. The glare constant for the whole installation will be the sum of the constants for the separate sources. Since the general background brightness B_b will be the same in every case, however, the glare constant for the whole installation can be expressed by:—

$$\text{Glare constant} = \frac{\Sigma(B_s^{1.6}\,\omega^{0.8})}{B_b}$$

The degree of discomfort under conditions of no visual task can then be found from the following table:—

TABLE 8

Values of Glare Constant and Corresponding Degree of Glare

K	Degree of Glare
>600	Intolerable discomfort
600	A. Just intolerable
600–150	Uncomfortable
150	B. Just uncomfortable
150–35	Distracting but not uncomfortable
35	C. Just acceptable
35–8	Acceptable but not imperceptible
8	D. Just imperceptible
<8	No glare

No numerical significance can be attached to the glare constant. It is merely an operator to translate the physical factors of the installation into the terms of the experimental subjective appraisal.

The values of the glare constant which apply under conditions of different visual tasks are not known with precision. It may eventually be possible to correlate the visual task with the glare constant. Appraisals so far made in schools and offices during the course of the investigation suggest, however, that for these and similar tasks no adjustments of the given values of the glare constant are needed.

It will be recalled that it was shown in Section IV(a) and Fig. 8 that the simple formula for the glare constant does not apply generally, but only to the straight-line portions of the S-shaped curves of Fig. 8.

In practice, this implies that the formula will hold for most artificial lighting fittings and for small windows, *but that it will not apply to large windows of high brightness.* The glare effects of sources of large apparent area are unfortunately too complex to

be constrained to fit a simple design formula. It should, however, be possible in due course to prepare tables based on the experimental data.

In order to modify an installation to meet a required standard of maximum tolerable glare, the glare constant for the unmodified installation is calculated as before. If the value so found is above that appropriate to the required standard, the installation is examined to discover the most fruitful means of modification (see Section VI (b)). A further calculation from the modified values will indicate if the necessary standard of freedom from glare has been achieved.

Example

A room has two windows 20 ft. away from the observer. One window measures 3 ft. x 4 ft. and looks out on to a part of the sky whose brightness is 1,000 foot-lamberts. The other window measures 2 ft. x 2 ft. 6 in. and has a sky brightness of 2,000 foot-lamberts. The general background brightness is found from inter-reflectance tables to be 50 foot-lamberts.

It is required to know if any discomfort due to glare will arise.

Source	(a) B_s	(b) $\log B_s$	(c) $1.6 \log B_s$	(d) ω	(e) $\log \omega$	(f) $0.8 \log\omega$	(g) (c) + (f)	(h) $B_s^{1.6}\ \omega^{0.8}$
Window (1)	1,000	3.0	4.80	0.03	—1.52	—1.22	3.58	3,800
Window (2)	2,000	3.3	5.28	0.01	—1.90	—1.52	3.76	5,700

$$\text{Glare constant} = \frac{\Sigma(B_s^{1.6}\,\omega^{0.8})}{B_b}$$

$$= \frac{\Sigma[1{,}000^{1.6}\,0.03^{0.8} + 2{,}000^{1.6}\,0.01^{0.8}]}{50}$$

$$= \frac{\Sigma[3800 + 5700]}{50}$$

$$= \frac{9500}{50} = 190$$

This value is seen from Table 8 to correspond to a degree of glare described as uncomfortable.

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Discussion

MR. S. A. W. JOHNSON-MARSHALL (Chief Architect, Ministry of Education) said that whilst he was grateful for being allowed to speak, he was probably, as an architect, one of the least qualified of those present to comment critically on this brilliant and significant paper. However, like so many designers, he was vitally concerned with the many implications of the paper which often did not occur to people like himself until there had been a good deal more instruction from their brother technicians.

His interest in this subject had originally been aroused during the war when he was engaged in the development of deceptive equipment for use by the Army in the field. They had tried hard to learn how, with the minimum of equipment, to make some objects invisible and some objects look more obvious. In that way, he believed he had learned a little about what the authors had called disability glare. He and those he then worked with were vaguely aware of discomfort glare and its subtleties but they realised how little they really knew. He believed that that state of affairs applied to a great many people in his profession. He was aware of it when the end of the war found him working with a group of architects under C. H. Aslin on a large programme of school buildings. Mr. Allen at the Building Research Station was consulted, and he very quickly introduced them to the two authors. Mr. Marshall said that intermittently since 1946 it had been his privilege to have the assistance of the two authors to the immense advantage of the buildings with which he had been concerned.

Throughout history probably painters—and in a great many cases architects—had been emotionally aware of discomfort glare and consequently their approach to the problem had always been empirical. As a result the development of satisfactory solutions had been very slow indeed. In the case of the Georgian window, for instance, it took a tremendous time to reach the high standard we now recognise.

Again, the recent development of windows in class rooms had shown that

requirements, technique, and architectural aspirations had led to the production of the large window which occupied practically the whole of one wall. This form of light source was advantageous to the children if they all faced in one direction with the source on their left. Modern teaching practice, however, often resulted in children working in small groups, for which purpose they wanted to face in any direction, including that of the main window. He suggested that if our knowledge of discomfort glare had remained purely empirical we should probably have had to abandon the large window with its many advantages because designers might not have been able to solve the problem of glare created by new teaching conditions. But thanks to the work of the authors the position was now fortunately very different.

The window was just one example of how knowledge now at the disposal of the designer enlarged his vocabulary and permitted him to evolve a higher degree of comfort and of beauty. Indeed, this work of the authors gave the architect a new order of freedom and he found it difficult not to praise it too much.

MR. A. T. PICKLES (Physics Division, Building Research Station) said that he also as a guest was grateful for the invitation to contribute to the discussion because it gave him the opportunity of giving an account of the background of research which led to the investigation of this type of problem. At the Building Research Station they were concerned, among other matters, with the problem of the assessment of the functional efficiency of buildings. It was necessary to know how good buildings were from the point of view of lighting, sound insulation, heating and ventilation, etc.; and whether or not it was true, as his architectural colleagues sometimes said, that a building was a machine to live in, there was one thing certain, and that was that a building was not lived in by a machine. Men were not mixtures of photometers, thermometers, microphones and calibrated amplifiers, and therefore those dealing with the functional efficiency of buildings were faced with the problem of using men to define the conditions. He viewed, therefore, this paper as an important one in relation to subjective study of all kinds. It is necessary to get measurements of the value of the heating and other installations in buildings, and to decide what the human requirements were.

There was one other aspect in which architects and others concerned with buildings were becoming increasingly interested, and that was that they were faced with the control of what was a naturally provided environment. For instance, daylight was a good thing and was provided free; the same applied to air movement. But in both cases it was obvious that an upper limit was necessary, and certainly it was possible to have too much air movement and, consequently, draught. In a number of fields there was the need for specification on the lines of what the authors had done in regard to lighting. This, however, was a matter for the future; lighting studies in his view were far more developed as regards the subjective aspect, as distinct from the engineering aspect, than the parallel studies in the fields of heating and ventilation, sound insulation and so on, and he congratulated the authors on what was a most important methodological paper applicable to a wide range of subjective studies.

MR. W. A. ALLEN (Building Research Station) expressed his appreciation of being allowed to pay a tribute to the work of his two distinguished colleagues. As an architect he felt that this work on discomfort glare had to be taken seriously because from the point of view of the development of architectural form and architectural tradition, discomfort was one of the major influences, much more so than, for instance, something like disability which did not necessarily affect the people who used the buildings and who therefore did not suffer in consequence. From the engineering point of view, disability might reduce the efficiency of a person using the building, but discomfort was generally a much more important matter to him because

it was more noticeable and so it came about that in the development of architectural tradition discomfort phenomena had always played a part. For this reason it was essential that in the new forms of lighting there should be reasonable freedom from discomfort. The aim must be to arrive at a sound basis for modern architectural design and that was where, in his view, the work described in this paper had a major contribution to make to the development of modern architecture.

That was one side, but there was another which Dr. Hopkinson had not mentioned. It was that discomfort might not be expunged merely because one liked comfort. We did not mind climbing a mountain or walking through the rain in considerable discomfort; but visual discomfort in a building leads to a quicker onset of tiredness and that was often a serious thing. There is not yet a laboratory measurement of the effect, but everybody dealing with this problem knew that it would cause tiredness quite quickly. The influence of a bare light source, such as the authors had demonstrated would, after a while, make one feel very unpleasant. Brightness grading in the environment was a matter which must receive a great deal more attention. He had noticed for four or five years that there was a difference between lighting fittings of about the same size and of about the same wattage depending on the extent of the grading. For instance, a translucent sphere compared with a prismatic fitting; it was noticeable how very much more comfortable a prismatic fitting was, and how this had escaped the general notice of people was a mystery to him. It was obviously going to affect lighting fittings as much as it had already begun to affect the design of windows.

There was one final remark which affected lighting people. Although Dr. Hopkinson had stressed that the limits of brightness in fittings were real limits, personally he did not like to think of people designing so close to a limit. He preferred that the aim should be an optimum, without getting anywhere near the limits unless absolutely necessary. That was something which architects were very anxious to see about fittings design, not merely avoiding the worst, but aiming quite definitely at the best.

MR. PATTERSON mentioned two points. The first was that, in his view, lighting should be designed not just for those with normal vision but also for those with subnormal vision. Under the new health scheme the use of spectacles was becoming more and more common and there were various points in relation to the wearing of spectacles which should be taken into account in lighting design. For instance, taking his own glasses which he should be used to by now, it was possible, if he were sitting with his back to a strong light source, to get as much glare by way of reflection in his glasses as if he were in direct vision to the light source. Also in the case of sunlight there was glare due to reflection in the rear surface of the spectacles which resulted in discomfort if not disability. Another point in connection with deep lenses was the apparent brightening of the lens due to high mounted light sources, the light entering the edge of the lens and affecting vision.

His other point related to the discomfort shadows and he suggested that this was also a matter which called for study.

MR. IMRIE-SMITH said that in reviewing the many efforts to appraise glare it would almost seem possible to plot a standard deviation curve of the formulae that had been evolved. There was one point which he had been endeavouring to visualise and which seemed to him must, in some form, be common to all systems, and that was that in dealing with the glare problem we must consider a certain limiting brightness. Glare is considered as a source of brightness contrasting with the brightness of the surround. The eye has a large light catchment angle and the tuning or adaptation of the eye would be a function of the gross amount of light it received. However the problem

was approached, it seemed to him that in the ultimate we got to the case where the eye is only adapted by a complete visual field of uniform brightness. The common result of research seemed to show that adding glare sources made the final result worse. If the process were continued, we would ultimately end up with a glare source the size of the visual field; the contrast would become nil, and it could be said there was no glare! but obviously this was a fallacious argument carried to extremes. The whole question, in a rudimentary way, appeared to be that glare was contrast and that therefore there was some relationship between the amount of light the eye received from the glare source and the amount of light which was received from the surround. On the other hand if a number of glare sources were put in, things were being made worse and worse but there would eventually be a field of brightness which might be intolerable or, on the other hand, it might be very acceptable. Somewhere our formulae have to cross over from a contrast to a brightness limit.

DR. W. S. STILES, remarking that it was very interesting to hear of this latest work on discomfort glare, said there were one or two technical points with regard to the experiments upon which he would like some further information. He believed that a fixation point was used but to what extent was the observer really looking in one direction in carrying out the work. He wondered whether this was quite what might be called a practical case because it seemed to him that in practice the eye would be wandering from point to point in the room. Perhaps this would not make a lot of difference to the experimental result, but he would like an answer.

Generally speaking, he said, it seemed to him remarkable how accurate these subjective criteria were proving to be. He had a good deal to do with measurements of a subjective character, measurements not based on subjective criteria in the sense the authors used the word, but based on the simple visual judgment whether or not something was visible—measurements of the visual threshold, in fact—but he did not think that under a given set of conditions with everything controlled he could get an accuracy which was better, than perhaps, .07 of a log. unit, and he believed the authors quoted 0.15 for the corresponding error in their subjective measurements. That was extraordinarily good because those who had been working in this field for some time had always, he thought, felt instinctively it was going to be very much more difficult to say when the conditions were just tolerable or just not unpleasant, than to say when an object was just visible. Experience was proving, however, that this view was wrong and he regarded this as a most important practical conclusion that had emerged from the work of the authors.

Another matter he had been very interested in hearing mentioned by the authors was the shock effect of a glare source. The authors had found that the brightness of a source was a rather less potent factor than Holladay had found by his technique which was based on the shock effect. It was realised that in the case of discomfort glare there was something in the nature of a local "irritation" of the retina. In discomfort glare we were not concerned with the action at a distance of a glare source imaged on one point of the retina on perception at another retinal point, but with a direct irritation of the retina where the glare source was imaged. Thus there were different laws for "shock irritation," and the "persistent irritation" of a glare source to which one had had time to become adapted.

His final remarks concerned the question of additivity. It was necessary to be a little careful in using the word additivity where non-linear relations came in. Whilst we were dealing with disability glare where the glare effect was a linear function of the source brightness or of the illumination produced by the source at the eye, additivity had an obvious interpretation, but now that there were various algebraical powers, for example, the power 1.6, creeping into the formulae it was essential to be careful to

know what was understood by additivity. He thought it was clearly set out in the paper but it was perhaps worth emphasising that we might have additivity when considering surround brightness as variable, but non-additivity when considering source brightness.

MR. A. G. PENNY remarked that in making their suggestions for much lower brightnesses of sources the authors should bear in mind that whilst almost all lighting engineers and designers were only too well aware of the fact that fittings were often too bright, they had to consider the manufacturing cost of fittings, how brightness fittings were generally either larger (and therefore more costly) or less efficient than bright fittings and the problem was essentially one of deciding, with the limited amount of money to be spent, whether to provide a fitting which would give a lot of light and some glare or a fitting which would give less glare and less light. It was very encouraging to see that the present I.E.S. Code came within the limits of the authors' suggestions for glare tolerance, and this suggested that as people became more and more willing to pay for good lighting, the designers of equipment would have no difficulty in bringing their designs into line with the proposals made by the authors.

MR. J. G. HOLMES asked for the authors' comments on two points which arose in the paper. Fig. 11 indicated that vertical angular displacement had very much the same effect as horizontal displacement but it had been his experience that upward vertical displacement was in fact very different from downward displacement. For example, glare reflected from a wet road below the direction of vision seemed more severe than that from high brightness street lighting fittings at the same angle above the direction of vision and, under daylight conditions, glare from snow-covered ground could be much more troublesome than that from an overcast sky. Fig. 10 in the paper showed that experiments had been made with sources at high angles above the horizontal and he wondered whether experiments might be made with the glare source below eye level.

The second point was that a coloured light might well give less discomfort glare than a white light of the same photometric brightness and intensity. As an example of this, there was in the Committee Room of the Lighting Service Bureau a glare source of considerable power consisting of an orange-red light surrounding the electric fire, but this was actually a comfortable light and he thought that the comfort came from the sense of warmth associated with the colour. In the experiments described in the paper there must have been a colour change when the lamps were dimmed or brightened and he wondered whether the authors had any evidence on the effect of this colour change and whether larger changes such as the use of "warm" lights or partial daylight correction would lead to reduction in discomfort glare.

Continuing, Mr. Holmes said that there were three questions he wished to ask in connection with the paper. Dr. Stiles had already mentioned the very satisfactory consistency of the results obtained by each of the selected observers and he wondered whether these six observers gave results which were consistent one with another, and what was the statistical significance of the absolute value of the glare factors under the conditions of these experiments. Secondly, the authors had made the point that, whereas disability glare was related closely to the intensity of the light source, the important property for discomfort glare was the brightness of the light source. He wondered whether this conclusion was based on a general survey of the observations because it did not seem to be supported by the glare formula which obviously related

to a limited range of the observations. The authors' formula can be rewritten as follows :—

$$K = \frac{I_s^{0.8} \times B_s^{0.8}}{D_s^{1.6} \times B_b} \text{ or } \frac{(E_s \times B_s)^{0.8}}{B_b}$$

where I_s is the intensity of the source in candelas

D_s is the distance in feet and

E_s is the direct illumination from the source at the observer in lm/ft.^{2}

It was obvious from these expressions that the intensity and the photometric brightness were equally important in the appraisal of discomfort glare and he thought from examination of the diagrams that the intensity would become the more important factor at low values of the glare constant.

Finally, he said that like Dr. Stiles he was somewhat concerned about the additive nature of the glare constant, and he wondered whether the authors could give, as an example, the method of computing the glare constant for the apparatus used in the demonstration of the effect of surround brightness which had been given in the presentation of the paper. In this demonstration there were two sources of the same order of area but of different photometric brightness and intensity, and he would like to know how the glare constant for the composite source could be computed when the brightnesses were different, and particularly when the outer source was about one-quarter the photometric brightness of the inner source.

MR. S. ANDERSON said there were two points upon which he would like some further information from the authors. The first was perhaps an extension of a point made by Mr. Holmes, but he regarded it as a practical one, concerning the influence of the direction from which the brightness came when one was measuring the discomfort or disability glare of a source of brightness. Mr. Holmes had mentioned the difference between glare due to a bright overcast sky and due to snow covered ground, but a far more common case which was met by everybody was where the brightness was to one side of the direction of vision. Had this case been considered ?

The second point upon which he would like some information was with regard to the class-room illustration given by the authors. He would be very interested to hear what sort of orders of brightness ratio existed in the class-room, which corresponded to the limiting conditions of the discomfort classifications given. He appreciated there were a wide variety of brightness contrasts from the different surfaces but what he regarded as most important were the brightnesses on the surface of the desks and on what appeared to be a diagram board on the wall.

MR. L. W. DAVIES asked if the authors could amplify the statement made by Mr. Holmes on the question of colour. He had always been under the impression that a reddish light caused quite considerable discomfort if there was a visual task being done for a long time. Mr. Holmes, however, seemed to think that a red colour would be more acceptable.

Another speaker had mentioned the possible discomforts when using spectacles but he believed there was an anti-reflection coating which could be used to eliminate any effect from the brightness of a light source.

G. V. DOWNER (*communicated*). While recognising and admiring the ingenuity and thoroughness of the authors in carrying out their experiments and collating the results in such an interesting and well-expressed paper, I feel a little disturbed at the apparent assumption that visible bright light sources, involving a good deal of glare, are bound to be used in all or most artificial lighting.

If this were the case, these investigations would be most necessary and useful, and

of course, in any case they would have their usefulness in the field of direct lighting, but I believe that that field should be much smaller than it is at present, and I regret the absence of any reference to indirect lighting. I should much like to see intelligent and enthusiastic engineers and scientists, such as the authors of this paper, devote their energies and the facilities at their disposal to discovering the most efficient, æsthetically satisfying and at the same time economical ways of applying indirect lighting to the innumerable conditions that may arise in practice. Instead of advocating, as the authors do, increasing the brightness of surroundings, in order to reduce contrast between source and surroundings, as the source is usually much brighter than it need be it would seem better, and incidentally more economical, to reduce the brightness of the source. However, with indirect lighting, of course, this problem could hardly arise.

DR. HOPKINSON, promising a detailed reply in writing, dealt with a few points raised in the discussion. He said that the authors very much appreciated the interesting discussion that had taken place on the paper and added that some of the questions that had been asked were actually answered in the paper, which, in the printed version, was quite different from the one that had been presented, and which had had to be shortened owing to limitations of time. Actually, in presenting the paper, the authors had dealt with it more or less generally in order to illustrate particular points.

Dealing with the point made by Mr. Patterson with regard to the effect of spectacles in aggravating glare, he said that this had not been neglected by the authors but no simple answer was possible. They had not been able to discuss all the experimental work that had been done, but it was hoped eventually to refer to some of these other matters.

In reply to Dr. Stiles the use of a fixation point depended on the experiment, but generally the point was only a guide as to where the observer should be looking. Where they were concerned particularly with the displacement of the source in the field of view, then the observer's line of vision was located more closely. The displacement of the source vertically and horizontally was something which needed further study, but actually it had been studied in greater detail than was reported in this paper. The essential thing which came into the problem was that the degree of glare from a source displaced from where the observer was looking depended very largely on the visual task. Most of the studies referred to in this paper were done with infinite background and no visual task and that accounted for the fact that the same results were obtained with both vertical and horizontal displacements. But in the street lighting studies employing a visual task, the angle of location was important. Further study was certainly advisable.

The question of additivity was dealt with in the paper but he thought that to solve Mr. Holmes's problem reference would need to be made to the data obtained on contrast grading. Dr. Stiles had given a timely warning that in considering additivity from the discomfort point of view the position was extremely complex. One of the jobs of the authors was to make it as simple as possible to apply the empirical glare formula and that was why they had made the "glare calculator" that had been shown.

Mention had also been made by Dr. Stiles of the degree of accuracy of these observations, and the fact that there was such a high degree of accuracy over long periods had also surprised the authors. In the past there had been a tendency for physicists, and perhaps engineers too, to discount the ability of man to act as a measure of his own surroundings, but if experiments were designed in which there were proper checks and cross-checks to make sure they were not getting unwanted trends creeping in unobserved, it was possible to make considerable use of man as an assessor of his surroundings. There was far more to this than the lighting problem alone, and the

authors hoped in due course to extend these techniques. It was hoped these studies would become more widely discussed, and that people concerned with subjective studies would get together and see if there was some sort of common ground and techniques which they could all use.

On behalf of his co-author and himself he expressed gratitude to Mr. Johnson-Marshall for coming along and discussing the paper. It was meeting people like Mr. Marshall and his colleagues who had definite jobs of work to do which acted as a stimulus to those concerned with the more technical problems; it prevented them getting fixed in the back room and not making contact with the practical realities of these problems.

As to the deviation between the different observers, mentioned by Mr. Holmes, it was of the order of .4 or .5, but that did not, of course, mean much among only six observers.

It was also asked by Mr. Holmes whether colour had any influence on the degree of discomfort. The authors did not study colour in this series of experiments because it had been found in street lighting that whilst the colour of the source did have some effect, one observer would assess a blue source as more glaring than an orange source and another would do the opposite. There was obviously something to be studied in this connection but the authors had not done it. However, it was believed from previous work that whatever effect there was it did not have more than a small effect on the experimental results of this particular study.

With regard to the question of brightness ratio mentioned by Mr. Anderson, the study of this problem of discomfort from glare was only one very small aspect of the whole problem of brightness distribution on which the authors were actively engaged. They were thinking now not in terms of glare, but in terms of the balance of brightness between one part of the visual field and another, and he hoped that this work would be of value to architects and lighting engineers. As Mr. Allen had indicated, there was a great deal to be done along these lines, and the authors felt that the subject was not limited to the glare problem. It went a long way beyond that and might well form the subject of the next paper which he hoped one day the authors would give to the Society.

THE AUTHORS (*communicated*). On reading the report of the discussion, there did not appear to be any major points left outstanding which are not dealt with in the printed version of the paper itself, but it might be of value to amplify Dr. Hopkinson's reply in one or two aspects. On the question of the additivity of glare source effects, the authors agree with Dr. Stiles and Mr. Holmes that one could not consider these effects additive in the sense ordinarily understood, and they hope that this is sufficiently pointed out in the paper. For some practical purposes, glare sources could be considered additive in the limited respects discussed in the paper, however, and the glare formula of Section IV(a) of the paper was given solely to assist the engineer to assess a glare problem to the first order of accuracy. For greater accuracy, or for the assessment of the glare effects of complex sources like those referred to by Mr. Holmes, the detailed experimental data itself had to be consulted. There is no other way at the moment. In addition, more study is needed of the effect of complex brightness backgrounds on visual comfort, but the authors hope that the experimental programme on which they are now engaged would prove useful in this connection.

Mr. Holmes's recasting of the glare formula serves to illustrate the relative effects of the various components. It will be recalled that this same recasting had been done for the previous paper on discomfort glare in streets. There is, indeed, evidence

to suggest that the discomfort glare from small sources is more dependent on their intensity than on their brightness. This is discussed in the paper.

There remain the points raised by Mr. Penny, and those communicated by Mr. Downer. In his remarks, Mr. Allen regretted the tendency to work down to a minimum standard. This tendency always results from regulations or codes of practice which specified lower limiting values, but, on the other hand, everyone realises how bad things would be in the absence of such lower limits. In lighting practice, however, two effects had resulted; one was to make people too "foot-candle conscious" the other was to determine the basic lines along which fittings were designed. The first effect is gradually giving place to a proper integration of lighting and vision, in which "foot-candles" played their proper but limited part. The second effect still influences fittings design in that the "efficiency" of a fitting is assessed in physical terms rather than in terms of its ability to produce good lighting in the surroundings for which it is designed. This is the basic difficulty against which Mr. Penny had to work. Freed from these limitations, designers were able to produce at reasonable cost, fittings which could give comfortable lighting and also adequate light for the visual task. As regards the indirect lighting solution advocated by Mr. Downer, indirect lighting had its places, but the majority of lighting problems were best solved by a less rigid approach, in which a proper balance of direct and indirect lighting was employed.

Obituary

H. HEPWORTH THOMPSON

It is with deep regret that we record the death on December 13 last of Mr. H. Hepworth Thompson, who was in his eightieth year. A member of the Society since 1927, he had long been connected with the lighting industry, having been managing director of Holophane, Ltd., for 25 years. He retired from that company in 1936. In 1939 he moved to Jersey, though within a few months he had to return to this country for the duration of the war.

Hepworth Thompson was President of the Society in 1934, and it must have been a source of some satisfaction to him that many of the developments which he proposed for the Society did in fact take place during his lifetime. He was one of the originators of the Fellowship scheme, though he did not himself apply for that distinction. He also felt that the work of the Society was not as well known as it should be, and he urged that steps be taken to give wider publicity to the Society and its activities. It is possible that during the last few years of his retirement he may have been out of touch with the increasing activities of the Society, but there is no doubt that during the 15 years between his term of office and his death the I.E.S. grew considerably in membership and prestige. The development of the Society to its present position is largely due to the efforts and foresight of members like Hepworth Thompson.

He leaves a wife, two sons, and a daughter, to whom the Society extend their sincere sympathy.

Additions to List of Members

The following applicants have been duly elected by the Council to membership in the Society, and their names have been added to the list of members.

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